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Feasibility of Green Roofs in the Main South Community of Worcester, Massachusetts

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Feasibility of Green Roofs in the Main South Neighborhood

An Interdisciplinary Qualifying Project

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Abstract

The goal of our project was to determine the feasibility of installing green roofs in two locations and determine other possible sites in Main South. Green roofs weigh 11 psf to 80+ psf. Roofs need to support their own weight, the green roof, and the code loads. Green roofs cost between $23/sf and $31/sf. There are 47 acres of flat roofs within the 450 acres of combined sewer area in Main South. We identified 57 possible green roof sites.

Executive Summary

Urban areas around the world are affected by numerous environmental problems which adversely affect the quality of life of their residents. Worcester, Massachusetts is no different. Poor air quality, the urban heat island (UHI) effect, and excess storm water runoff all impact the residents of the Main South neighborhood. Widely known for its building innovations, the Main South Community Development Corporation (MSCDC) has sought to address quality of life issues through the implementation of green technologies in their neighborhood revitalization projects. This project explores how green roofs might be a logical next step for the MSCDC to explore. The goal of our project was to determine the feasibility of green roofs on two buildings in Main South, the MSCDC garage located at 24 Kilby Street and the WCUW radio station building located at 910 Main Street. In addition to assessing the feasibility of these buildings, we also examined other flat-roofed structures in the neighborhood. This executive summary covers some background information regarding environmental issues and green roofs, our project objectives and methods, and our key findings.

Background

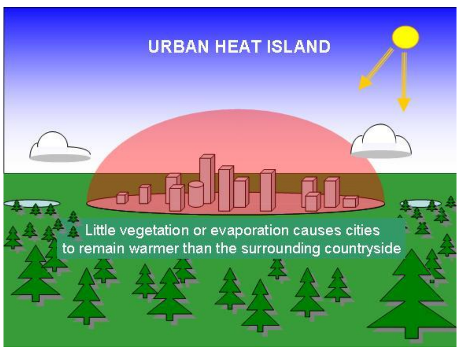

Figure 1: Urban Heat Island Effect

http://www.weatherquestions.com/urban_heat_island.jpg

Heavy traffic volume and the high demand for energy, in conjunction with little green space, result in a decreased air quality, an increase in temperature, and the UHI effect, shown in Figure 1. Storm water is also an increasingly important issue for the neighborhood. A large area of Main South lies within the city's combined sewer system (CSS), which drains both storm water and sanitary waste through the same lines (see Figure 2). During heavy rainfall these lines are overwhelmed which causes them back up and flow into city streets.

The Main South CDC has been a leader in revitalizing the Main South neighborhood for over 20 years. In an effort to help the community to become more sustainable, the MSCDC incorporated the use of green technologies in its projects for over a decade. Some examples are the use of non-toxic building materials, energy efficient windows and appliances, and installed photovoltaic (PV) panels. Most recently, they have installed rain water collection systems and residential cogeneration systems in their projects. Given the environmental and social issues that affect the community, green roofs may be the next logical step for the MSCDC to explore.

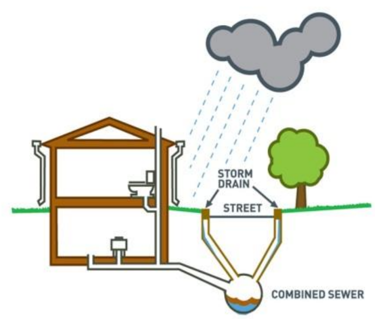

Figure 2: CSS

http://www.msdgc.org/wetweather/why_do_sewers_overflow

According to the US Environmental Protection Agency (EPA), green roofs are, "rooftops planted with vegetation…" (*Glossary* 2009). There are many different types of green roofs, and they vary in price, weight, and materials. The two main categories are intensive green roofs, which have soils depths of more than 6", and extensive green roofs, with soil depths less than 6". Within these categories, there are two main styles of green roofs: traditional, shown in Figure 4 and modular, shown in Figure 3. All green roofs help to combat the urban and environmental issues affecting cities, provide energy savings, and extend the lifetimes of the roofs. They can weigh anywhere between 11 and 80 pounds per square foot (psf), and are usually installed on flat roofs. The combination of urban environmental issues green roofs can combat and the potential for energy savings make them viable options for implementing green infrastructure in the Main South community.

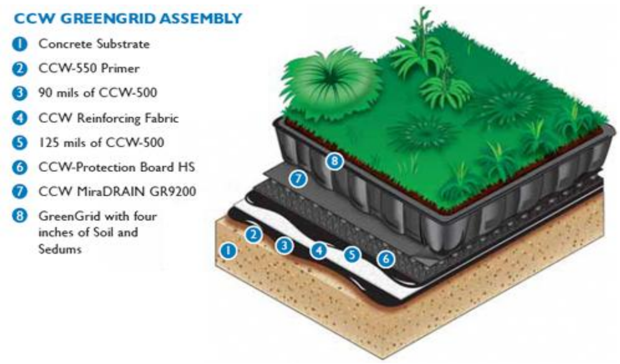

Figure 3: Modular Green Roof

http://www.carlisle-ccw.com/findsolution/productcategory.aspx?cat=30

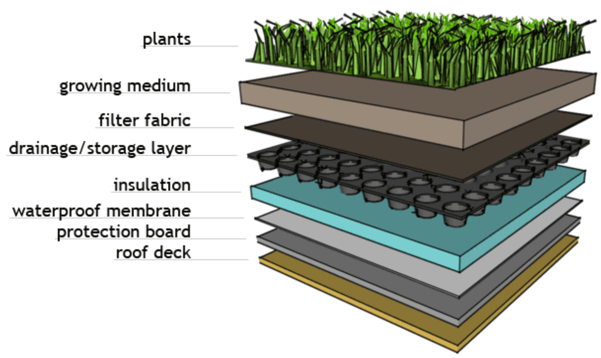

Figure 4: Traditional Green Roof

http://greengarage.ca/greenroofs/features.php

Methodology

In order to achieve our goal we carried out the following steps:

- Determined the weight ranges of typical green roofs;
- Determined the structural capacities of two existing roofs;
- Determined more specific criteria about what makes a building suitable for a green roof;
- Determined the average cost associated with green roofs in this area;
- Identified other potential sites for green roofs.

These steps allowed us to reach our goal of determining the feasibility of green roofs in two locations and to identify other potential sites within Main South.

Findings

This section outlines the results and findings from our objectives. It includes information on the support requirements of a green roof, the strength of a structure that can hold a green roof, the cost of a green roof, and further site identification. These areas build upon each other to create a database from which further research can be conducted.

Green Roofs not Feasible for Either of Our Buildings

Our structural analyses revealed that neither the MSCDC's maintenance garage nor the WCUW Radio building would be able to accommodate the additional weight of a green roof without significant structural modifications. We reached this conclusion through hand calculations, computer simulations, and conferring with an expert. Table 1 shows a summary of the maximum allowable loads along with the loads green roofs would place on the structures. It can be seen that the allowable loads for the

WCUW building and the MSCDC garage are 22 psf and 49 psf, respectively, and that the total loads with green roofs are 79 psf and 81 psf, respectively. Figure 5 and Figure 6 show the results of the ANSYS simulation run on both trusses. The members in dark blue are the critical members and dictated the maximum allowable loads.

Table 1: Summary of Loads

	WCUW Radio (psf)	MSCDC Garage (psf)
Allowable Load	22	49
Current Dead Load	13	15
Snow Load	55	55
Min. Green Roof Load	11	11
Total	79	81

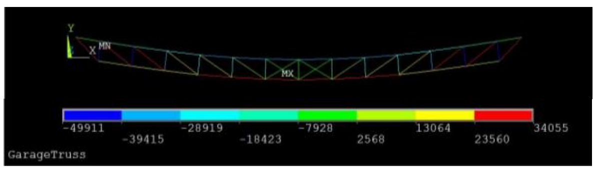

Figure 5: ANSYS analysis of CDC Garage

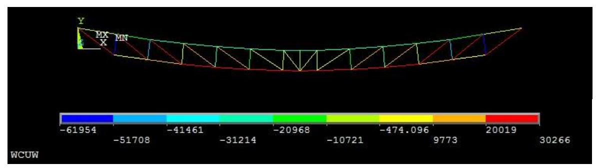

Figure 6: ANSYS analysis of WCUW building

Both buildings would need extensive structural modifications if green roofs were to be installed. With the potential for other sites that will not need modifications, it is cost-prohibitive to modify the buildings because of the high costs of hiring a structural engineer and the costs of the modifications.

Cost Analysis

We have found the cost of a green roof in the Main South community to be between $23-40 per square foot, with an associated cost savings of between 10-30% on energy. We also provided a cost estimate of a conventional roof for comparison. The prices in Table 2, which are explained below, are meant to provide a basic cost estimate of four roof systems, not to give a precise cost.

Table 2: 50 Year Cost Analysis

	Conventional	4” Modular	8” Modular	4-8” Traditional
Energy Savings	N/A	10-30%	10-30%	10-30%
Structural Engineer	N/A	10k-20k	10k-20k	10k-20k
Green Roof Design and Manufacturing	N/A	$11-15/sf	$18-27/sf	$7-9/sf
Roofing Membrane	$5-7/sf	$5-7/sf	$5-7/sf	$5-7/sf
Green Roof Installation	N/A	$7-9/sf	$8-10/sf	$11-13/sf
Total w/out Modifications	$5-7/sf	$23-31/sf	$31-40/sf	$23-29/sf
10,000 sf Roof w/out Modifications ($)	50k-70k *2= 100-140k	240k-330k	320k-420k	240k-310k

The cost of a structural engineer was estimated to be between $10,000 and $20,000. There are many factors that could affect this price including: the availability of building plans, the complexity and age of the building and the susceptibility of snow drift on the rooftop. These factors make the structural analysis difficult to estimate without a specific site, but we have concluded that the price will most likely be within our given range.

The costs of green roof design and manufacturing as well as installation were based on prices provided to us by industry professionals. The cost per square foot decreases with larger roof areas. For this given design and manufacturing price, the manufacturer will design the soil and vegetation, and deliver the materials to the site. For modular systems, the manufacturer will also plant and grow the vegetation for 4-6 months, which explains the higher cost. However, the installation cost for the modular systems was the cheapest because it consists of simply placing the modules in place. A traditional intensive green roof is cheaper to manufacture, but the installation is more expensive since it includes planting all the vegetation on site. When the prices for design and manufacturing are combined with installation, modular and traditional green roofs cost approximately the same.

The cost of a single ply roofing membrane that is typically placed under green roofs is about $5-$7 per square foot. Since we only considered existing buildings we assumed that the membrane needs to be replaced. Placing a green roof on top of an existing roofing membrane is not recommended because it would void any roofing warranty and also require a labor intensive process to replace the roofing membrane once a green roof is installed. The roofing material will also last about twice as long with a green roof than without due to the UV protection that the plants and soils provide. So, for the smartest investment the owner should hire one contractor to replace the membrane and install the green roof. It is important to consider because for a 10,000 sq. ft. building the roofing membrane is about $60,000 which would need to be done regardless. Also, since green roofs can double the lifetime of the roof the owner is saving the $60,000 that it would cost to replace it. So in that regards, the owner can consider $120,000 of the cost to be inevitable.

Every building is going to generate different energy savings sue to the many different variables such as: heating source, air conditioning unit, number of stories, and insulation. If the 10,000 sq. ft. building spent $10,000 annually on heating and cooling, and its conditions created 30% savings, then the owner would see a return on the investment in approximately 34 years.

Additional Sites in the Neighborhood

We determined that in Main South there are approximately 160 buildings that have flat roofs and are located within the confines of the CSS. We only identified buildings within the CSS since storm water retention would provide a greater impact on residents prone to sewer overflow. Figure 7 is a map of Main South that shows the locations of these buildings and the confines of the combined sewer system. On the map, the borders of the Main South neighborhood are shown in pink, and the extents of the combined sewer system are shown in blue. We calculated the area of the combined sewer in Main South to be approximately 450 acres. All the buildings that have flat roofs, which cover approximately 50 acres, are identified by the green rectangles in Figure 7. Given the number of buildings with flat roofs and the substantial area they cover, we believe that further investigation of green roof feasibility in Main South should be pursued.

Figure 7: Possible Future Sites within Main South's CSS

Of the 160 buildings with flat roofs, we have further investigated 58 for their potential of green roof installation. We ranked the buildings based on the following criteria: existing building structure, visibility of the roofs, size of adjacent sewer pipes, and area of the roofs. Table 3 shows these criteria. We set the ranking up so that the structural properties of each building were weighted highest, twice as important as the roofs' visibilities and areas. We then weighted the sewer pipe size category to be the average between the structural properties and the visibility. We left the final category, owners' interest, open to be very subjective, assigning the three ranks no numerical values. We did this because the cooperation and willingness of building owners to invest in their property many times determines whether such a project can move forward.

Table 3: Ranking system

Rank	Structural	Visibility	Pipe Size	Roof Area	Interest
0				0-4999	
1	Wood Residential	Not visible	30"	5000-6999	Low
2	Wood Commercial	Poorly Visible	20"-28"	7000-9999	Neutral
3	Masonry Residential	Moderately Visible	13"18"	10000+	High
4	Masonry Commercial	Highly Visible	9"-12"		
5	Brick Residential		8"		
6	Brick Commercial				
7	Steel Residential				
8	Steel Commercial				

Our results, shown in Table 4, provide a list of numerous sites in Main South which have the potential for green roof installation. We have also identified the potential interest of the property owners in Table 4. It also shows an initial estimate of the cost of a green roof, if one were to be installed. It is our hope that the MSCDC and other developers use these rankings to further investigate the possibility of installing green roofs in Main South.

Table 4: Top 58 Identified Sites

Rank	Address	Owner	Structure	Visbility	Pipe Size	Roof Area	Interest	Total	Low Cost	High Cost
1	65 Tainter	The Boys & Girls Club	6	6	3	3	High	18	$734,500.00	$996,500.00
2	12 Queen	UMass Medical Center	6	5	4	3	High	18	$417,100.00	$568,700.00
3	26 Queen	UMass Medical Center	6	5	4	3	High	18	$525,200.00	$714,400.00
4	33,39,43 Hammond	New Method Plating & Enameling	6	5	4	3	Neutral	18	$613,796.00	$833,812.00
5	44 Hammond	Nettle LLC	6	5	4	3	Neutral	18	$1,059,950.00	$1,435,150.00
6	93 Grand	Main South CDC	6	6	2	3	Neutral	17	$977,150.00	$1,323,550.00
7	662 Main	MGM Pena LLC	6	5	3	3	Neutral	17	$1,241,236.00	$1,679,492.00
8	857 Main	Roman Catholic Bishop of Worcester	6	5	3	3	High	17	$508,525.00	$691,925.00
9	888 Main	Arthur Mooradian, Trustee	4	5	4	3	Low	16	$345,823.00	$472,631.00
10	689 Main	Sondatt B Prashad, Trustee	6	5	3	2	Neutral	16	$171,000.00	$237,000.00
11	95 Grand	Worcester EOEND	6	5	2	3	Low	16	$956,450.00	$1,295,650.00
12	653 Main	Hadley Apartments LLC	5	5	3	3	Neutral	16	$297,500.00	$407,500.00
13	45 Grand	Crystal Park Ltd Partnership	5	5	3	3	Neutral	16	$1,398,004.00	$1,890,788.00
14	49 Gardner	South Garden Realty Inc	7	6	2	1	Neutral	16	$149,564.00	$208,108.00
15	674 Main	Worcester Lofts Limited Partnership	6	5	3	1	Neutral	15	$134,200.00	$187,400.00
16	701 Main	PIP Foundation Inc	5	5	3	2	Low	15	$185,950.00	$257,150.00
17	845 Main	J & M Batista Family Limited	7	5	3	0	Low	15	$52,366.00	$77,102.00
18	875 Main	Clark University Trustees	4	6	3	2	High	15	$235,216.00	$323,552.00
19	19 Ripley	Crozier Inc.	6	2	4	3	High	15	$319,350.00	$436,950.00
20	64 Beacon	Vaios Theodorakos, Trustee	6	2	3	3	Low	14	$1,372,750.00	$1,856,750.00
21	98 Beacon	Steven M Rothschild, Trustee	5	2	5	2	Neutral	14	$173,875.00	$240,875.00
22	18 Hammond	Idak Convalescent Centers Inc.	5	5	4	0	Neutral	14	$84,865.00	$120,905.00
23	35 Lagrange	Joseph M & Stephen A Krosoczka	7	2	5	0	High	14	$119,250.00	$167,250.00
24	47 Lagrange	Sem Tec Inc	4	2	5	3	High	14	$311,185.00	$425,945.00
25	50 Lagrange	Joseph M & Stephen A Krosoczka	6	2	5	1	High	14	$135,580.00	$189,260.00
26	698 Main	Ediberto Santiago	5	5	3	1	Neutral	14	$154,900.00	$215,300.00
27	891 Main	Raymond A. & Judith Levine	6	5	3	0	Neutral	14	$81,369.00	$116,193.00
28	712 Main	Wellington Company	5	5	3	1	Neutral	14	$168,700.00	$233,900.00
29	945 Main	Clark University Trustees	4	5	3	2	High	14	$230,800.00	$317,600.00
30	14 Gardner	Lisa D Servant	5	5	3	0	Neutral	13	$84,060.00	$119,820.00
31	12 Hammond	Alfred Roy and Sons Inc.	5	5	3	0	Neutral	13	$28,216.00	$44,552.00
32	68 Gardner	68 Gardner LLC	4	5	1	3	Neutral	13	$1,409,320.00	$1,906,040.00
33	24 Kilby	Main South CDC	3	5	4	1	High	13	$148,000.00	$206,000.00
34	650 Main	Anastasios Karamanos	4	5	3	1	Neutral	13	$126,081.00	$176,457.00
35	660 Main	Community Renewal, Inc	3	5	3	2	Neutral	13	$171,345.00	$237,465.00
36	667 Main	General Realty Corp	3	5	3	2	Neutral	13	$205,500.00	$283,500.00
37	709 Main	Julio Romero	4	5	3	1	Neutral	13	$149,840.00	$208,480.00
38	720 Main	Chestnut Renewal Cooperation	5	5	3	0	Neutral	13	$93,950.00	$133,150.00
39	895 Main	Gordon J Turpin	5	5	3	0	High	13	$77,068.00	$110,396.00
40	108 Beacon	HW Beacon LLC	5	2	5	0	Neutral	12	$110,050.00	$154,850.00
41	22 Ethan Allen	Wellington Company	5	0	5	2	Neutral	12	$206,650.00	$285,050.00
42	868 Main	Quek Kevin Ying Xuan	3	5	3	1	Neutral	12	$162,720.00	$225,840.00
43	931 Main	Roman Catholic Bishop of Worcester	4	5	3	0	High	12	$85,670.00	$121,990.00
44	46 Wellington	Wellington Company	5	0	4	3	Neutral	12	$259,550.00	$356,350.00
45	872 Main	Zi Feng Li	3	5	3	0	Neutral	11	$81,116.00	$115,852.00
46	880 Main	Cultural Ctr Hrisohorafiton	3	5	3	0	Neutral	11	$96,020.00	$135,940.00
47	6 Ripley	Main South CDC	5	2	4	0	High	11	$99,999.00	$141,303.00
48	25 Ethan Allen	Wellington Company	5	0	5	0	Neutral	10	$85,900.00	$122,300.00
49	9 Hammond	All Realtime Realty LLC	2	5	3	0	Neutral	10	$27,871.00	$44,087.00
50	64 Jackson	US Sprint Communications Company	4	1	4	1	Neutral	10	$137,351.00	$191,647.00
51	934 Main	Clark University Trustees	2	5	3	0	Neutral	10	$101,770.00	$143,690.00
52	45 Wellington	Chestnut Renweal Cooperation	5	0	4	0	Neutral	9	$59,105.00	$86,185.00
53	49 Wellington	Chestnut Renweal Cooperation	5	0	4	0	Neutral	9	$96,250.00	$136,250.00
54	36 Gates	Main South CDC	2	1	5	0	High	8	$65,660.00	$95,020.00
55	23 Wellington	Wellington Company	5	0	3	0	Neutral	8	$116,720.00	$163,840.00
56	37 Wellington	Chestnut Renweal Cooperation	5	0	3	0	Neutral	8	$58,300.00	$85,100.00
57	1 Kilby	Garry G. Dutram	2	1	4	0	Neutral	7	$79,000.00	$113,000.00
58	767 Main	Standish Apartments Ltd Partner	5	5	2	0	High	12	$118,100.00	$165,700.00

Summary

The two buildings that our project focused on, the MSCDC's maintenance garage, and the WCUW Radio building, were deemed not feasible for green roof installation with their current structures. We then identified alternate sites within Main South to be further investigated for green roof installation. It is our hope that with further investigation of these sites that green roofs could become a real possibility in the Main South Community. If this all takes root, our project will have served as a catalyst towards getting green roofs installed throughout the community and an important first step towards improving the quality of life for the residents of Main South.

Authorship:

We certify that all members of the project team have contributed equally to the completion of this project.

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Introduction

Urban areas throughout the world are affected by numerous environmental problems which adversely affect the quality of life of their residents. These issues, such as poor air quality, the urban heat island effect, and excess storm water runoff, all impact people living in urban areas. Due to the large volume of vehicles in and around cities, as well as the numerous buildings' mechanical systems, harmful emissions such as green house gasses have been released into the atmosphere at rates never before seen. This has led to a decrease in air quality in urban areas. Another environmental issue plaguing urban areas is the urban heat island (UHI) effect. The UHI effect causes the temperatures in urban areas to be greater than those in rural areas. The temperature difference can be as much as 22 degrees Fahrenheit (Fischetti, 2008). Additionally, because of the large amount of impervious surfaces in urban areas, storm water runoff is also a problem. This is particularly prevalent in the Main South neighborhood of Worcester, Massachusetts. A large portion of Main South lies within Worcester's combined sewer system, which must discharge excessively or can back up into city streets during heavy rainfall. Currently, there are ongoing efforts to help combat these issues within the Main South community.

The Main South Community Development Corporation (MSCDC) is a nonprofit organization that has been working for over 20 years and is leading the way in the revitalization of the Main South neighborhood. The MSCDC has been implementing green technologies in recent redevelopment projects. They have started to combat urban environmental issues through the use of local building materials, energy efficient windows and appliances, and solar photovoltaic (PV) systems. The MSCDC has also begun to investigate residential cogeneration systems, and rain barrels to harvest storm water runoff. With the mission of making Main South more sustainable, the MSCDC has not only been using green technologies on its own projects but is encouraging others to follow suit. To achieve this goal, the MSCDC is always looking for new options to explore.

Green roofs are a logical next step for the MSCDC to explore in promoting and implementing green technologies in Main South. According to the US Environmental Protection Agency (EPA), green roofs are, "rooftops planted with vegetation…" (*Glossary* 2009). There are two main types of green roofs, intensive and extensive. Intensive green roofs have soil depths greater than six inches, and extensive roofs have soil depths less than six inches. Although the types of green roofs vary, they provide the approximately same benefits. The plants absorb carbon dioxide and emit oxygen, helping to improve air quality. They also work to reduce the UHI effect by providing more natural surfaces to reflect heat. Green roofs provide both financial and environmental benefits to building owners, by reducing the average heating and cooling demand by 10-30% because they provide more insulation and do not absorb as much heat as a conventional black roof. Green roofs also retain between 50-70% of rainfall on a roof, releasing it over time or through evaporation.

The goal of our project was to determine the feasibility of green roofs in several locations in the Main South neighborhood. We investigated two buildings, the MSCDC's garage located at 24 Kilby Street, and the WCUW radio station building, located at 910 Main Street. These locations were chosen because of their high visibility, and were meant to serve as demonstration sites to educate residents and promote future green roofs within the community. In addition to our investigation of these two buildings, we also moved forward to identify other sites within the community. We looked at structures within Main South which had flat roofs and identified and ranked many for further investigation into the feasibility of green roof installation on those buildings.

This report covers background material, project objectives, project methods, and findings. The literature review provides extensive information on the urban environmental issues facing the Main South community. It also explains what the MSCDC is, gives details into their mission and past redevelopment projects and use of green technologies, and explains what green roofs are and how they can be used to combat these issues. The methodology section covers the objectives we used to achieve our goal in this project. It shows the steps we took to fulfill these objectives. Our findings section explains in detail what we have determined through our methodology, and provides some recommendations for further research of green roofs in the Main South community.

Literature Review

Introduction

The current urban environmental issues affecting the community have led to a decreased quality of life for residents. In order to combat this, the MSCDC was created, and is now implementing green technologies in the community. Thus far, they have used nontoxic local building materials, installed energy efficient windows and appliances, installed solar panels, installed residential cogeneration systems, and begun to implement rain water collection systems. The next logical step for them to take in making Main South a sustainable community is implementing green roofs, which according to the Environmental Protection Agency (EPA) green roofs "are rooftops planted with vegetation…" (*Glossary* 2009). The Main South Community Development Corporation hopes to use these initial green roofs as a stepping stone for others in the community and city. This section will provide an analysis of the driving factors behind the implementation of green roofs in low-income urban environments.

Urban Environmental Issues

Today, the state of the environment is an important issue in urban areas around the world. In many cities, urban environmental issues negatively affect residents' lives. Issues such as poor air quality, flooding and the urban heat island effect are the main ones affecting people. Worcester and the Main South neighborhood are no exception to these problems.

Air pollution is one area of concern. Cities typically contain elevated levels of air pollutants that can be harmful to both human and environmental health (Yang, Yu, & Gong, 2008). Urban areas are often the source of many greenhouse gases (GHGs) because of the density of traffic, homes, stores, and human life in general. GHGs trap heat emitted by the sun within Earth's atmosphere, and so unchecked human-caused emissions lead to more heat being trapped within the atmosphere and ultimately a global warming (*The Causes of Climate Change*, 2010). As the world's population continues to grow, urban air pollution will become an even larger issue. "Since 1950 the world population has more than doubled, and the global number of cars has increased by a factor of ten. In the same period the fraction of people living in urban areas has increased by a factor of four" (Fenger, 2002). Due to high population density in urban areas, millions of people are inhaling these pollutants on a daily basis for much of their lives.

There is a wide range of health risks associated with urban air pollutants. They range in severity but in extreme cases; can lead to early deaths (Cohen et al., 2004). Add this to its global impact and it is clear that people need to be taking action to reduce air pollution in urban areas. Since the Clean Air Act was passed in 1970, the EPA has regulated the emission of pollutants. They have been successful in lowering pollution rates and limiting damage done by factories and large producers of harmful chemicals, but have not focused on ridding the air of existing pollutants (Cohen et al., 2004). To have the largest effect on improving urban air quality, cities must strive to go above and beyond what is required by regulations.

The addition of more vegetation throughout a city also contributes to improving air quality and reducing pollution. Trees, shrubs, grass, and all other forms of plant life are natural air purifiers. By producing oxygen and absorbing various types of harmful greenhouse gases, plants have the potential to make a large impact on air quality. In Yang's study of green roofs in Chicago, he notes, "the high surface area and roughness provided by the branches, twigs, and foliage make vegetation an effective sink for air pollutants" (Yang, Yu, & Gong, 2008). By adding green roofs to buildings throughout the city, Chicago has made strides in reducing the amount of air pollution and improving the air quality in and around the city. Vegetation is valuable in urban settings because it removes pollutants already in the air as well as pollutants continuously being given off by humans. This leads to a reduction in air pollution and helps to improve the quality of life of residents where green roofs exist.

An additional effect of the increased temperatures resulting from Global Warming is increased rainfall. As the National Geographic's website puts it, "Precipitation (rain and snowfall) has increased across the globe, on average" and this is expected to continue (Effects of Global Warming, 2010). As mentioned earlier, increased rainfall means increased sewage intake and higher treatment costs. Since many environmental issues are growing stronger with time, it is imperative that cities look for lasting solutions to improve their environments.

Urban areas are covered with impervious surfaces, which create large amounts of storm water runoff. In rural areas, rainfall is naturally absorbed into the Earth by plants and soils. However, urban areas typically have large amounts of sidewalks, paved roads and parking lots, and impervious rooftops. All of these surfaces are examples of materials that do not allow water to be absorbed by the Earth. In regards to impervious surfaces, Berghage noted that, "Not only is total volume of WWF [Wet Weather Flow] increased, but peak flow rates are also increased" (R. Berghage, D. Beattie, A. Jarrett, C. Thuring, F. Razaei, 2010). As water runs over paved surfaces it absorbs pollutants such as salt, dirt, and oil. Eventually, most of the rainwater makes its way into the sewer system where it is treated and discharged into local waterways. The runoff created from large amounts of impervious land creates a great deal of pressure on a city's sewer system.

A similar urban environmental issue created by impervious surfaces is the urban heat island (UHI) effect (see Figure 8). The UHI effect is caused by the nature of urban development. Peck and Richie make the observation, "In metropolitan areas, urban development has replaced much of the vegetated landscape with built structures and surfaces, altering near-surface climate and causing air temperatures to increase"(Peck & Richie, 2009). This describes what has happened in almost every city and densely populated urban space in the world. As increasing numbers of homes, businesses, and infrastructure begin to occupy smaller spaces, the vast majority, if not all, of the natural landscape is lost. The UHI effect is the increase in ambient air temperature as a result of modifying a landscape that was able to reflect heat, such as a forest, to create one that absorbs it, such as a parking lot, sidewalk, or tar roof. Most common building materials, such as asphalt, concrete, and waterproofing materials, absorb the Sun's energy and convert that energy into heat. This conversion can lead to temperatures in developed urban areas that can climb as much as 22 degrees Fahrenheit higher than in rural areas in the same parts of the globe. Many times what comes to mind when people think of a highly developed urban area is a major city and its surrounding suburbs, such as Boston, Massachusetts and its neighbors. However, even cities with populations less than 100,000 are impacted by the UHI effect (Peck & Richie, 2009).

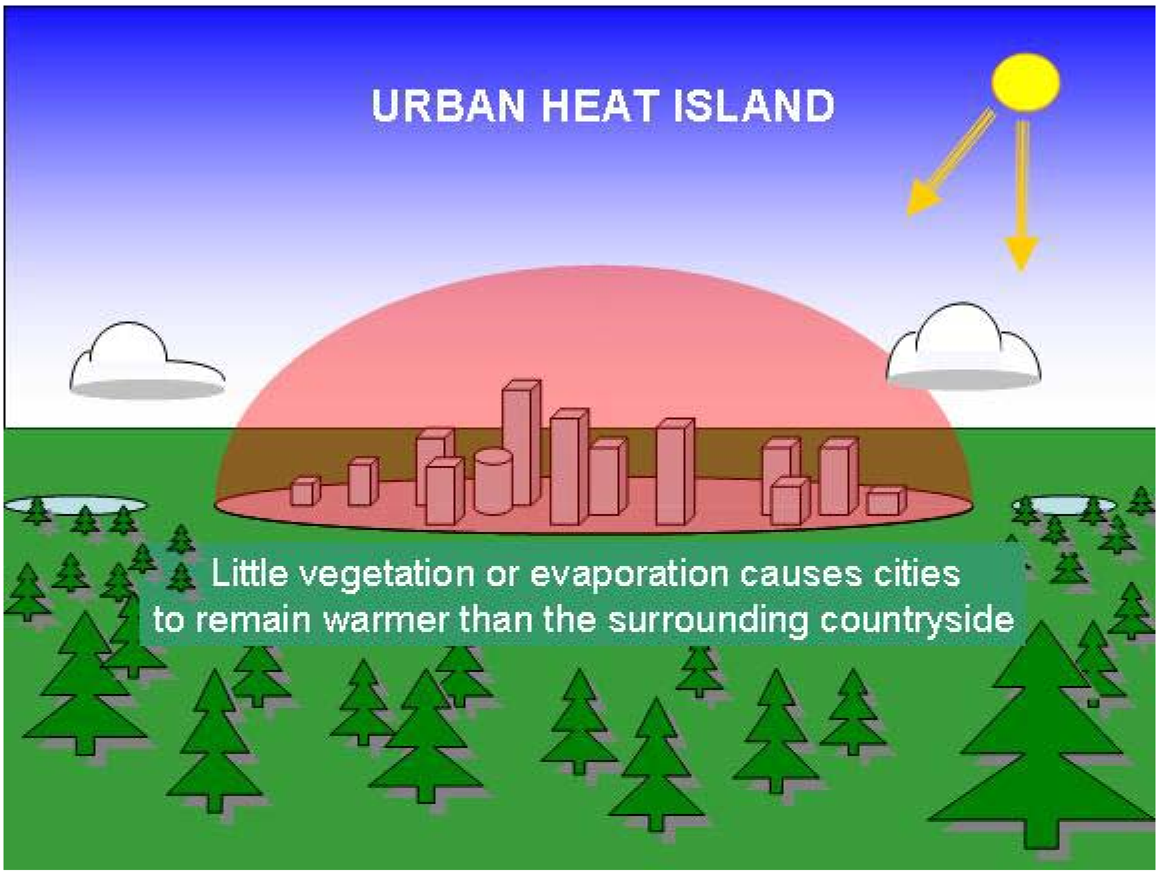

Figure 8: The UHI Effect
http://www.weatherquestions.com/urban_heat_island.jpg

The Main South Neighborhood Environment

The city of Worcester, Massachusetts suffers the same environmental impacts felt by larger urban areas. In the Main South neighborhood, these environmental issues can be combated. Exhaust from vehicles and other harmful chemicals are emitted in larger quantities in urban areas, creating harmful air pollution. The large percentage of land covered by impervious surfaces creates excess storm water runoff, which can strain sewer systems. These paved surfaces, along with those on the roofs of buildings, absorb heat instead of reflecting it, creating what is known as the UHI effect. These issues, which are all present in the Main South neighborhood, contribute to decreasing the quality of life of residents of Main South.

The sewer system in Worcester is made up of three distinct and separate components. They are: the sanitary sewer system, which handles sewage; the storm sewer, which channels surface water runoff from properties and streets to the nearest river, stream or lake; and the combined sewer system (see Figure 9), which “collects both sewage and storm water and conveys it to the Upper Blackstone plant for treatment before it discharges to the Blackstone River” (K. Eliadi, 2010). Some sections of Worcester’s combined sewer system, which covers an area of four square miles, have been around since the mid 19th Century (K. Eliadi, 2010). In the past, combined sewage passing through this system would flow untreated into the Blackstone River whenever there was a heavy rainfall. This was a result of the large volume of water overwhelming the system’s pipes’ and treatment facility’s capacities. Now, it is first treated at the Quinsigamond Avenue Combined Sewer Overflow Treatment Facility (QACSOTF) before being discharged (K. Eliadi, 2010).

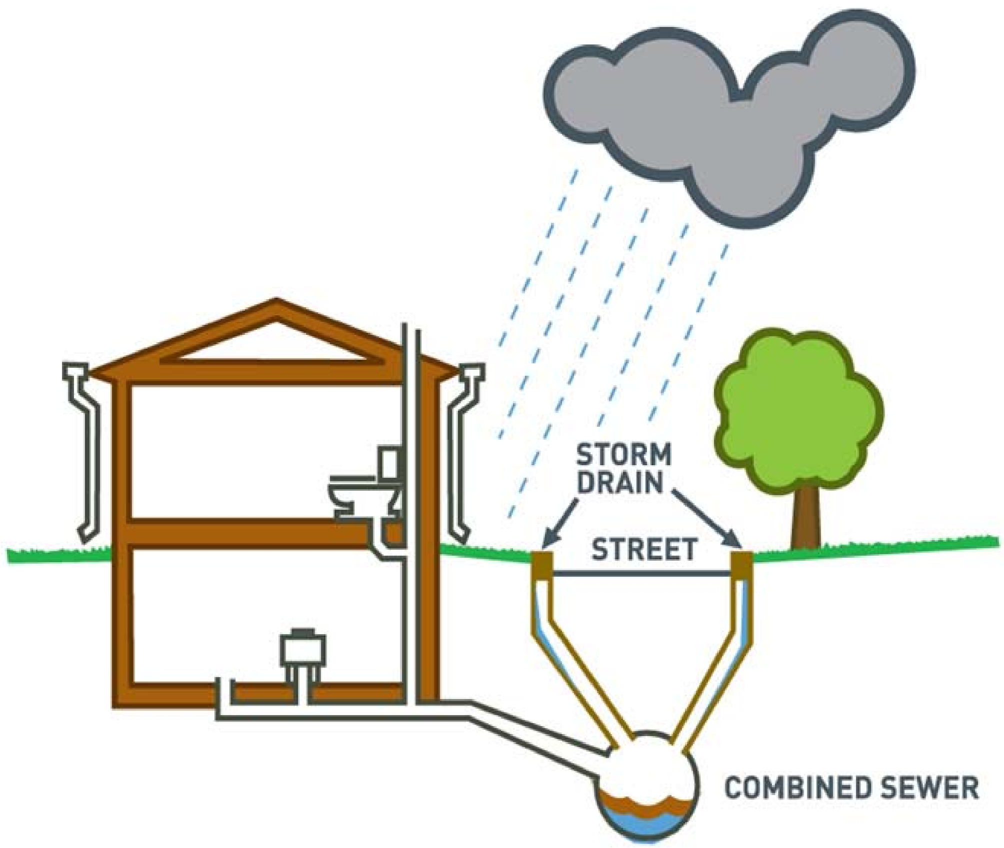

Figure 9. Diagram of a Combined Sewer System
http://www.msdgc.org/wetweather/why_do_sewers_overflow.htm

The QACSOTF must function according to federal and state regulations during periods of both high and low surface runoff. During low runoff, it channels the predominantly sewage mixture to the Upper Blackstone Treatment Facility; and when there is high surface runoff, the facility treats the sewage-runoff mixture and then discharges it into “the former Mill Brook and eventually discharges into the Blackstone River” (K. Eliadi, 2010). Because the facility deals with the discharge of sewage into the Blackstone River, its operations are regulated by the EPA and the Massachusetts Department of Environmental Protection (MassDEP). These agencies place limits on the types and amounts of certain contaminants that the QACSOTF discharges, especially phosphates and nitrates (K. Eliadi, 2010). Runoff entering the QACSOTF may contain high levels of phosphates (P. Middaugh, personal communication, September 9, 2010). There is also an attempt to have limits placed on the frequency of such discharges, which is proving to be very problematic for the City of Worcester, since they have “yet to master control of the weather” (K. Eliadi, 2010).

Efforts are being made by the City of Worcester to meet the requirements of the EPA and MassDEP. These include modifications that have been made to the structure of the Green Hill Pond to increase its capacity and reduce the volume of storm water, thus making it possible for combined sewage to be slowly fed to the QACSOTF (K. Eliadi, 2010). However, “ways to separate storm water from sewage may exist [but] many of these options are too costly. Cost-effective combined sewer separation projects will be considered but it is beyond the financial capabilities of the city and its ratepayers to move forward with a wholesale elimination of the combined sewer system” (K, Eliadi, 2010). As a result of the hindering cost factor, a worthwhile option is finding ways to reduce the amount of storm water runoff that enters the combined sewer system. Since traditional storm water management methods tend to require large amounts of space and are costly to implement, new strategies need to be developed to lower the intake of Worcester’s combined sewer system. Less storm water runoff added to the combined sewer would reduce the frequency of discharges into the Blackstone River by the QACSOTF and help meet the standards set by the EPA and MassDEP.

The Main South neighborhood in Worcester experiences the negative effects caused by the UHI effect. Main South is in the middle of the city where the temperatures are theoretically higher. While no data for multiple areas within the Main South neighborhood and Worcester is available, temperatures for locations within three miles of the MSCDC proving the UHI effect can be had (see Table 5). On November 11, 2010 at 3 pm, the temperature in the more built-up Pakachoag, Auburn, MA was 2.2 F higher than that on that town’s plant-rich golf course.

Table 5: Temperatures at Nearby Locations on November, 11, 2010 at 3:00 pm.
http://www.wunderground.com/US/MA/Worcester.html#PWS

Station Location	Temperature
Pakachoag, Auburn, MA	52.0 °F
Cherry Valley, Cherry Valley, MA	50.3 °F
Pakachoag Golf Course Vicinity, Auburn, MA	49.8 °F

The UHI effect can also cause the economy to slow down. As temperatures rise, tourism can be affected negatively (Peck & Richie, 2009). People generally do not want to sight see or even leave their homes during intense heat. Additionally, people aspire to move further away from the city to escape the heat (Peck & Richie, 2009). This causes wealthy citizens to move to suburbs, leaving mostly low income housing for urban areas. By combating the UHI effect in the Main South neighborhood it could lead new residents and investors to look into the possibility of redeveloping dilapidated and run down properties in the area as it would become more appealing for residents and visitors alike.

Urban areas can be largely affected by their environments. The neglect of environmental issues can cause many harmful effects, which are being seen today. The air that people breathe is plagued with pollutants. Excess impervious surfaces force water to run across dirty city streets and enter the sewer system for costly treatment and release. The loss of the natural landscape causes heat to build up and elevate inner city temperatures. The production of greenhouse gases throughout cities adds to global climate change. One way to combat the urban environmental issues is with green technologies, which have already begun to be incorporated into the Main South neighborhood. However, if the neighborhood is truly going to be sustainable, the next logical step is to go further and explore more green technologies that can help the community. Green roofs are a part of that next step. As Peggy Middaugh said, "this project all goes back to quality of life" (P. Middaugh, personal communication, September 9, 2010). Green roofs can provide numerous quality of life benefits, which will all contribute to helping with the revitalization of Main South.

Green Roofs: Combating Urban Environmental Issues

Green technologies have already begun to be incorporated into the Main South neighborhood. However, if the neighborhood is truly going to be sustainable, the next step is to go further and explore more green technologies that can help the community. Green roofs could be a major part of that next step. Issues such as air pollution and storm water runoff can be addressed through the use of green roofs in the community. More important, however, to the residents of Main South, and to people and businesses looking to move there, is the issue of quality of life. The drive to implement green roofs throughout the community can lead to a higher quality of life.

Green Roofs- Options

A green roof- shown in Figure 10- is an alternative to a traditional roof that, "involves the placement of low-maintenance, hearty plants, such as sedum, along with grasses and other smaller plant species on top of an existing roof membrane" (Kravitz, 2006). Green roofs are the perfect tool for combating the aforementioned environmental concerns. There are two main types of green roofs, intensive and extensive. Intensive green roofs have deep soil (6 inches or more) to support a wide variety of plant or tree species, while extensive green roofs have much shallower soil depths (6 inches or less), to support turf, grass, or other types of ground cover (*Glossary* 2009). Intensive green roofs are usually very heavy, which would require structural modifications to be made to most buildings, and usually require considerable maintenance. Extensive green roofs, on the other hand, are lightweight and can usually be installed directly on the existing roof membrane, requiring no modifications to be made to the building's structure. Also, due to the shallow soil depth and the usually extreme environment on many roofs, the plants selected are normally very sun-, weather- and drought resistant, which leads to little maintenance associated with an extensive green roof (Kravitz, 2006).

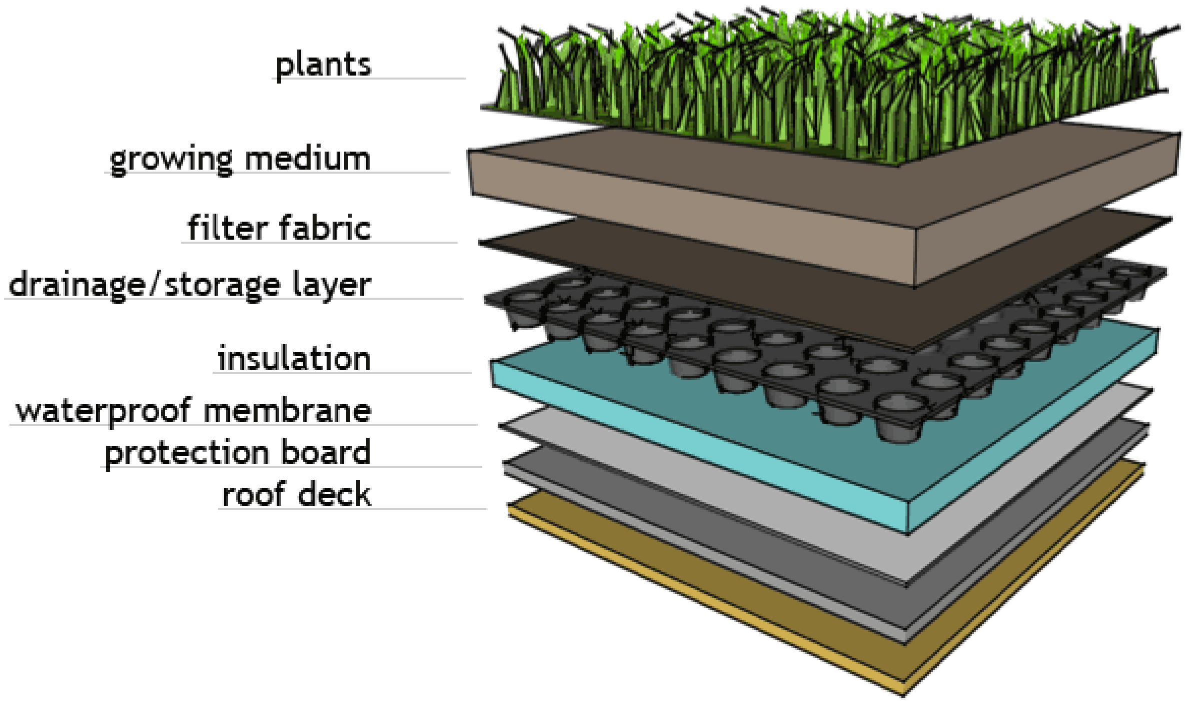

Figure 10. Typical Layout of a Green Roof
http://greengarage.ca/greenroofs/features.php

Within the realms of intensive and extensive green roofs, there are even more options for how to achieve design goals. Weston Solutions' GreenGrid© System is a modular system that can be structured to be considered either an intensive or an extensive system (see Figure 11). Apex Roofing uses a "mat" system which is similar to sod used by landscapers to quickly have full grown vegetation in a new location (See Figure 12). Weston Solutions and Apex Roofing along with many other contractors also provide intensive "bath tub" options. All of these systems have advantages and disadvantages; it is important to consider what the goal of the green roof is when beginning to choose the correct system (C. Terrio, telephone communication, October 28, 2010).

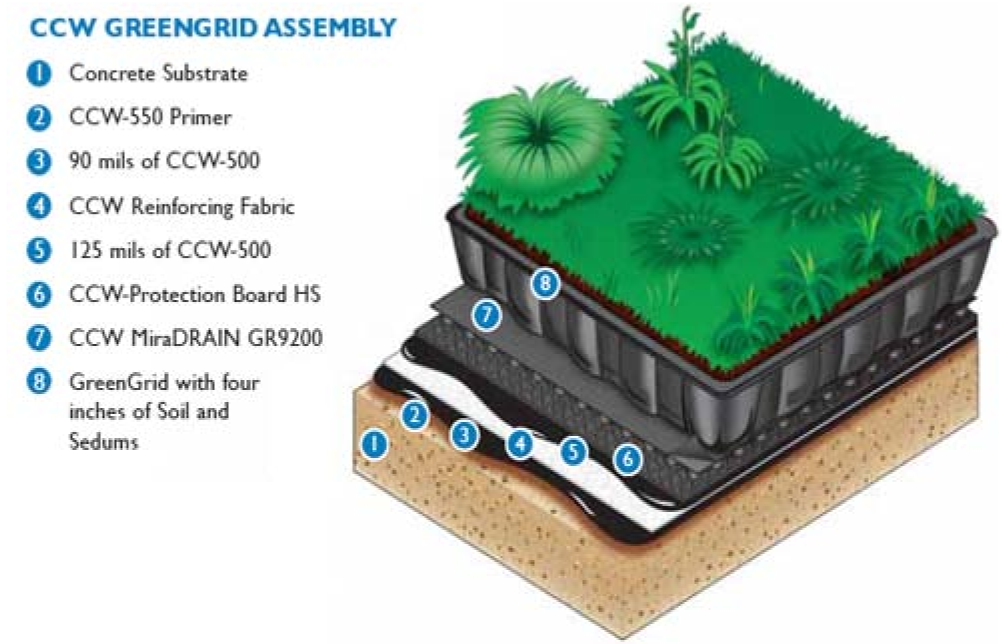

Figure 11. Modular Green Roof System
http://www.carlisle-ccw.com/findsolution/productcategory.aspx?cat=30

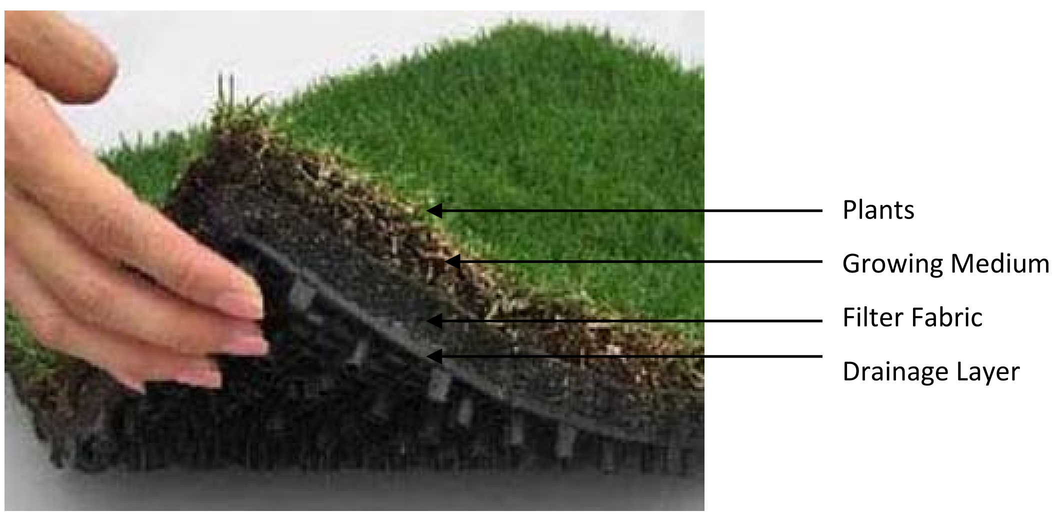

Figure 12. Green Roof Mat System
http://greenz.jp/en/2010/07/14/green-roof-tiles-from-toyota-roof-gardens/

Green Roofs – Design Criteria

When designing a green roof, it is important to consider design criteria. We identified the major problems in the Main South Community to be excess storm water runoff, UHI effect, increased energy costs, and lowered quality of life. To account for storm water runoff, the roof should be able to hold back as much storm water as possible. To combat the UHI effect, the roof should have the greatest amount of vegetation possible because plant life reflects heat. To help lower heating and cooling costs the growth media must be deep enough to regulate the internal temperature of the building. Figure 13 shows thermal properties of green roof systems of different depths. It is important to note the negligible difference between the eight inch and four inch systems. When WPI entrusted the design of East Hall's green roof to Cannon Design, one of their objectives was to provide a platform for researching storm water runoff from green and conventional roofs (L. Deninger, telephone communication, October 28, 2010). Cannon Design decided to use Weston Solutions' GreenGrid© system.

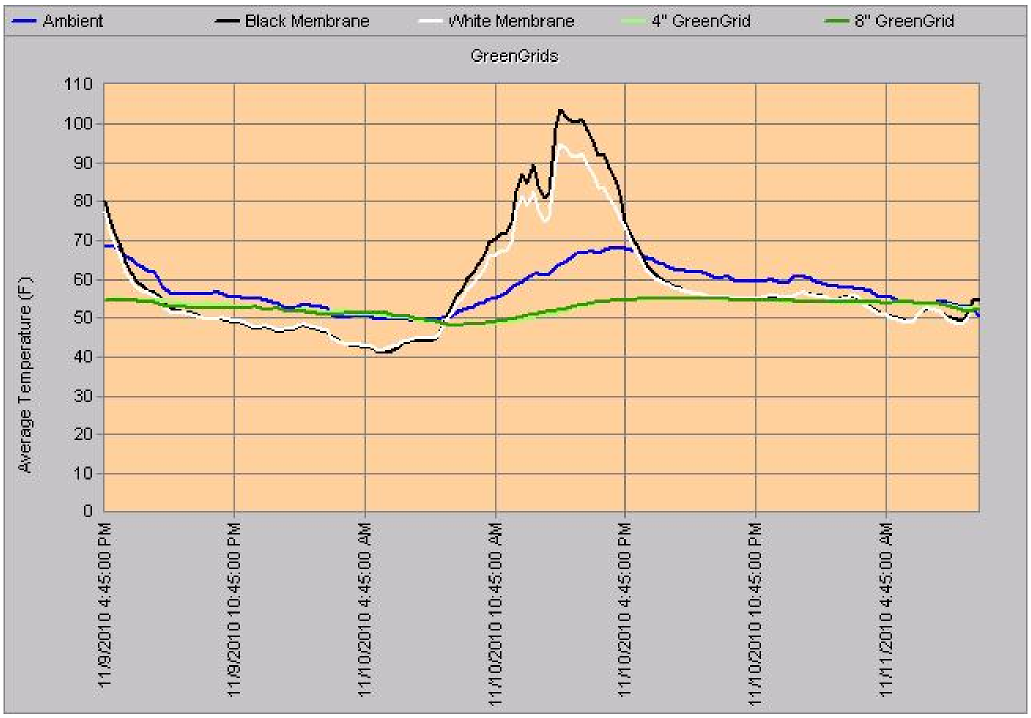

Figure 13: Negligible differences between eight inch and four inches of growth media
http://www.greengridroofs.com/

Weston Solutions' GreenGrid© modular green roof system contains trays in which plants are planted off site at a nursery. This allows the plants to mature until they reach a point where they can safely be put into a harsh new environment without a high risk of death. Then they are transported to the rooftop and put into place. There are specific plants which thrive in rooftop conditions due to their drought resistant nature, wind tolerance, and growth media needs. Other factors to consider when choosing a modular system include the depth of soil in regards to weight and desired vegetation. The growth media commonly selected for modular systems is comprised of organic and inorganic material that provide the needed nutrients for the plants selected for that particular location.

Through ongoing research on WPI's East Hall's green roof, it has been suggested that water runoff from green roofs has a higher phosphate concentration than traditional roofs. The growth medium can be formulated in order to produce a minimum amount of phosphates in the runoff. However, the reduced volume of runoff from green roofs may be great enough to offset this difference. If phosphates are a concern during green roof design, there are options to harvest of filter runoff, such as rain barrels or filtration systems (D. Pellegrino, personal communication, October 28, 2010).

Green Roofs -Cost

The three main factors affecting the cost of a green roof are installation, maintenance, and energy savings. Ideally, energy savings will be greater than the cost of installation and maintenance. This would allow the roof to pay for itself before needing to be replaced. Due to the widely varying types of green roofs available, the costs for installation and maintenance also vary greatly, as do the returns in energy savings. The national average cost of an intensive green roof is 25 to 40 dollars per square foot, while it is between 14 and 25 dollars per square foot for extensive green roofs (Carter & Keeler, 2008). In Michigan, it was found that a low-cost green roof can provide a return on investment of 11 years (Herman, 2010). This proves that green roofs can be cost-efficient and also provide positive impacts on the environment.

Green Roofs- Benefits

The thermal insulation properties of a material are summarized in what is referred to as an R-value. It is not possible to identify the R-value for a green roof due to the changes in moisture content. These changes create a variety of conditions which not only change the thermal conductivity of the media, but also change the bulk temperature of the material. According to data from Weston Solutions, there is a negligible difference in the fluctuation of interior temperature between four inch and eight inch depth modular systems. One disadvantage to a modular system is the gaps between the trays, intended for irrigation systems, which can lower the thermal insulation provided by the roofing system. Green roofs can provide cost benefits in other ways than simply saving on heating and cooling.

Green roofs provide an additional layer of protection for the waterproofing membrane installed on the roof. The growth media and vegetation provide protection from ultra-violet (UV) rays which can cause cracking and damage the membrane. This damage can cause leaks and eventual damage to the underlying supporting structure. While there is no guarantee that green roofs provide complete protection against leaks, they provide one more layer of protection. With the added protection of a green roof, the 25-year lifespan of traditional roofing membranes can be improved to 50-75 years. If access to the roof is needed for the repair or replacement of damaged or defective waterproofing membranes, modular systems can be easily removed and staged elsewhere while the repairs are made. With non-modular systems the process of removing the growth media is very labor intensive and thus very expensive.

One of the main contributing factors to urban quality of life is air quality (Clark, Adriaens, & Talbot, 2008). “Green roofs are a tool to help address the issue of air quality affecting quality of life in an urban setting.” (Myers, 1988). Green roofs do not reduce the number of cars on the road or make vehicles with cleaner emissions, but by increasing the vegetation in areas normally void of plant life, they help decrease the levels of carbon dioxide in the air. Large scale movements to install green roofs have substantially aided in improving air quality and reducing pollution. “Plants and trees absorb CO_2 as they grow, ‘sequestering’ carbon naturally. Increasing forestlands… could increase the amount of carbon we're storing,” and reduce the amount being emitted directly and indirectly via energy savings (Herman, 2010). It has been recognized that the amount of GHGs (including carbon) being emitted into the Earth’s atmosphere needs to be reduced if the planet is going to remain livable as we know it today. By absorbing carbon and other harmful gases and releasing oxygen into the air, the plants used in green roofs are another useful tool useful in reducing the amount of GHGs in the air.

In addition to combating GHGs, green roofs also help to reduce the amount of impervious surfaces present in a given area (R. Berghage, D. Beattie, A. Jarrett, C. Thuring, F. Razaei, 2010). With storm water runoff becoming an increasing concern to many in the environmental community, any reduction in the amount of surface area for water to runoff is helpful. This reduction in impervious area has been shown to lead to the retention and/or removal of up to 50% of storm water runoff by way of evapotranspiration (R. Berghage, D. Beattie, A. Jarrett, C. Thuring, F. Razaei, 2010). Additionally, green roofs can decrease, “the peak rate of runoff from the site” (R. Berghage, D. Beattie, A. Jarrett, C. Thuring, F. Razaei, 2010), which can help prevent flooding caused by a heavy or prolonged rainstorm. Green roofs help to filter-out pollutants existing in water runoff, which in turn causes the amount of polluted water entering sewer systems and waterways to decline (R. Berghage, D. Beattie, A. Jarrett, C. Thuring, F. Razaei, 2010). In addition to improving the quality and reducing the volume of storm water runoff, green roofs can help to reduce the UHI effect.

The increased temperatures caused by the UHI effect can be a problem for an area such as Main South. Not all of the residents are able to afford air conditioning to cool their homes during the hot summer months, and those that have it may not be able to afford to use it. According to Steven Peck, founder and president of Green Roofs for Healthy Cities, “A 1 degree C. increase in summer temperatures has been correlated with a 3.8-percent increase in peak demand load for air-conditioning” (R. Berghage, D. Beattie, A. Jarrett, C. Thuring, F. Razaei, 2010). Additionally, reversing the UHI effect has been shown to greatly reduce the cost of air conditioning. Most large air conditioning units are located on rooftops, and they lose efficiency as the intake temperature increases (Peck & Richie, 2009). “According to Environment Canada… a garden roof with about 10 centimeters (3.9 inches) of growth would reduce cooling needs by 25 percent” (Hasan, 2009). Green roofs can help with this by reflecting the heat caused by UHI, which helps to lower temperatures in the city. On a typical 80-degree-F day, a black rooftop can reach 180 degrees F, a white rooftop can reach 120 degrees F, and a vegetated roof only reaches 85 degrees F (Fischetti, 2008). Green roofs also provide much better insulation than traditional roofs, which can lead to keeping heat inside homes in the winter and keeping it out in the summer, thus lowering the cost of climate control (Clark, Adriaens, & Talbot, 2008).

Although green roofs are more complicated and costly than their traditional counterparts, the numerous positive effects they have make them worthwhile investments. It has been shown that although green roofs are more expensive to install than traditional roofs, they provide various savings and can even provide a return on investment given the right conditions. The effects they have on the environment are also positive- by reducing the amount of carbon in the atmosphere and reducing the amount of impervious surface in urban areas, green roofs contribute to improving air quality and reducing storm water runoff. Green roofs also provide energy savings to the inhabitants or tenants of the buildings they are located on, reducing not only the cost of air conditioning and heating, but also the need for them as well. This is done through the added insulation of green roofs, which reduces heat loss from and heat gain to the building. These are just some ways in which green roofs help to improve quality of life.

Project Stakeholders

A number of organizations have a vested interest in the conducting of this project and the subsequent implementation of the green roofs. Three of these are: the Main South Community

Development Corporation (CDC), the WCUW Radio station and the Regional Environmental Council (REC). Below, we have outlined the background and reason for interest in the project for each organization.

Main South Community Development Corporation-Background

The Main South neighborhood is a lively and diverse community. However, due to its location in downtown Worcester, Main South experiences environmental and economic problems commonly present in urban areas. According to the census for the areas represented, 23.3% of the families live below the poverty level, and of homes with children, over 27% of the families live below the poverty level. From the same cross section, 64% of homes have a female head of household *(Main South Community Development Corporation*, 2010). One thing that could lead to change in these areas would be an increase in the quality of life through increased income from jobs and reduced amounts paid in taxes.

This is why in May 1986 a team of individuals put together what has become a thriving and well organized neighborhood revitalization effort, the MSCDC. The MSCDC is a 501 (c) (s) non-profit organization formed in 1986 by local residents' who were concerned about the declining state of their neighborhood and the growing shortage of affordable housing (*Main South Community Development Corporation*,2010). According to the MSCDC's website their mission is:

> To improve the quality of life for ourselves, our families, and our neighbors by working together on projects and issues that will maintain and/or create safe affordable housing for low-to-moderate income individuals, support economic opportunities for businesses and residents of Main South, enhance the physical image of the area, and instill a sense of neighborhood pride and commitment *(Main South Community Development Corporation*, 2010).

This mission statement paves the way for the numerous areas and projects currently occurring through the MSCDC.

Main South Community Development Corporation-Projects

In order to help with general revitalization of the Main South area, the MSCDC has improved dilapidated houses and helped to reuse abandoned commercial space. The MSCDC has ongoing projects to provide residents with affordable housing. They are able to offer this housing because of their many years of work restoring commercial and residential properties. This has fostered a "rebirth of Main South" (*Main South Community Development Corporation*, 2010). The current projects within this rebirth are: Foreclosure Mitigation, which uses federal funds to redevelop five to six foreclosed properties a year; 1 Wyman Street, which utilized local labor to redevelop a mixed commercial and residential property in 2009; 189 Beacon Street: the Youth Build Program, which will educate local youth on sustainable construction and renovation while renovating a foreclosed single family house; and 93 Grand Street, an industrial site formerly occupied by Crompton and Knowles Loom Manufacturing Company, for which the MSCDC has received EPA grants to clean up and develop the 1.7 acre property. These individual projects are all a part of the MSCDC's longstanding redevelopment plan (*Main South Community Development Corporation, 2010)*.

The newest project that the MSCDC has put a great deal of time and energy into is the Kilby Gardner Hammond Neighborhood Revitalization Project. This project is a futuristic and bold redevelopment plan which is a model for urban communities around the country. The basics of the project include turning an under-developed inner city area with numerous vacant lots into an affordable housing corridor for first time home buyers. All of the newly constructed homes are built with green materials and include solar panels on the rooftops and rain barrels to collect storm water runoff (*Main South Community Development Corporation*, 2010). Within the neighborhood, the MSCDC also assisted with the construction of a new Boys and Girls Club and has plans for a new athletic field for Clark University. The end result will be a vibrant, clean, safe, and sustainable area located on a once abandoned block of Main South.

In order to make its changes last, “the Main South CDC also works for change on a political and legal level” *(Main South Community Development Corporation*, 2010). The objective behind this kind of work is to promote long term change that will help the community prosper. In accordance with this mission, their goals include: home ownership for low-income residents, enhancing the image of the local community, fostering pride in the neighborhood, seeking membership for a cross-section of residents and business owners in the community, and operating as a democratic organization.

The MSCDC recently received a grant from the EPA that would provide it with the financial backing to implement and educate about green technology around the community. As important as it is to install rain barrels, green roofs, and solar panels, it does little good if the people in the community surrounding the technology do not understand their importance in raising the standard of life in the community (M. Starr, personal communication, September 9, 2010).

In addition to these redevelopment projects the MSCDC also hosts community events to help grow community pride and develop a sense of stewardship. They have a ‘First-Time Homebuyer Program’, which “offers individuals with low to moderate income an opportunity to purchase a newly renovated home in the Main South area” (*Main South Community Development Corporation,* 2010). The MSCDC also offers home improvement loans, down-payment assistance loans, small business loans, and technical assistance. These many support services are all a part of the Neighborhood Revitalization Strategy Area (NRSA), which is sponsored in part by the city of Worcester, and which aims to provide residents with the assistance they need to improve their lives and the lives of those around them *(Main South Community Development Corporation*, 2010). Another area where the MSCDC strives for improvements is public safety; they work closely with the Worcester Police Department and also host public safety meetings to help prevent criminal activity. Along with these programs, the MSCDC also brings education to the community, provided in part by Clark University. These classes began in 2002 and to date approximately 500 individuals have completed courses. The MSCDC sponsors social and recreational activities for the community. This combination of events and activities helps keep the community involved in the physical restoration, and also aids in forming the necessary sense of community pride needed to create a thriving community.

All of the efforts of the MSCDC are aimed at increasing the quality of life of community residents. Using green energy will help to combat urban environmental issues and increase sustainability. There are currently many ongoing projects which will increase quality of life for residents. The MSCDC is trying to educate Main South’s residents so that the change they help to implement will have a greater impact.

WCUW Radio

WCUW is a locally supported radio station that caters to the needs of its local supports and listeners. They are strongly invested in the community in which they are located and try to provide the best services possible to their listeners (*Community Radio for Global Audience,* 2010). WCUW hosts elections for local residents to serve on its board of directors, thus showing their investment in the community. Also, they host concerts in the community which can help to foster pride in one's community. WCUW is a great resource to help spread information and motivation through the community because of its ability to communicate with so many people at once. Adding a green roof to their building will benefit those directly around them and help to foster quality of life improvements in their community. It will also insulate their roof and aid in reducing their heating/cooling costs.

Regional Environmental Council

The Regional Environmental Council (REC) is another stakeholder invested in improving the quality of life in the Main South community. They sponsor programs with youth to help raise awareness of environmental injustice. One of its major programs supervises youth in the growing and cultivation of crops, which could possibly be grown on rooftops. The REC is also interested in educating these youth in other areas of agriculture. They have not worked with any green roof infrastructure, but did express an interest in looking further into it.

Two of these organizations, the MSCDC and WCUW Radio, have decided to embark on this project, because it is in line with their missions. They aim to improve the quality of life- surrounding environment, infrastructure, etc. - of the residents of the Main South neighborhood. The resulting report will be taken to the organization's financiers with the aim of finding funding for the roofs to be built. After the roofs have been built, they will then use their resources to embark on an educational campaign geared at getting the community excited and involved enough to implement their own green roofs. Once implemented, these green roofs will begin to reap the benefits outlined above.

Summary

Urban areas are currently being plagued by a variety of environmental issues. These environmental issues have a negative impact on quality of life in an urban setting. The implementation of green technologies has proven itself to be effective in combating both environmental and quality of life concerns if done on a large scale. The Main South Community Development Corporation has undertaken an effort to implement these technologies on a local scale in order to better the community's quality of life and set an example for how to implement these technologies in an affordable and practical way. Through this section, the driving factors behind installing green roofs in low-income areas have been identified and explored.

Methodology

Introduction

The following section outlines how we achieved our project goal. To help us achieve our goals, we established a set of objectives. We initially had three objectives, to perform structural analyses on each of the buildings, to design three green roof options for each building, and to provide a cost analysis. As our project progressed, we added more objectives. The first was to determine the load requirements for green roofs and the second was to identify alternative sites in Main South which have potential for further investigation. These objectives were accomplished simultaneously. We used mostly quantitative research; however some qualitative research was also conducted. Quantitative research was conducted in order to provide statistics on green roof effects, the cost analysis, and structural analysis since we needed specific data to produce our calculations. Qualitative research is needed for green roof designs and also the initial directions of how to conduct a structural analysis because we were less familiar with these topics and did not completely understand them until research began.

Objective One: Determine Load Requirements for Green Roofs

Determining the typical weights for green roofs was important because we needed to know approximately how much weight we would be adding to the roofs when the structural analysis was finished. To do this, we examined a WPI Master Qualifying Project (MQP) report on sustainable landscaping, conducted research about green roofs, and consulted professionals from green roof companies.

We identified Weston Solutions as the area leader in modular green roofs. Their online resources did not have the necessary information we needed; therefore, we contacted Mr. Jared Markham and Ms. Melissa Bezanson. Mr. Markham was Weston’s project manager for both the John W. McCormack Federal Building in Boston and WPI’s East Hall. We inquired about the weights of their company’s roofing trays. After conducting research on a different form of green roofs, again the proprietary information was not located online; therefore, we contacted Mr. Dustin Brackney from Apex Green Roofs, to determine the weight range of his company’s green roof systems.

In addition to determining the weights of the soil and plantings themselves, we also determined the weights of the various additional roofing membranes needed to support a green roof. The wide range of membranes available made it necessary to talk with an expert about what was correct for a job similar to ours. We spoke with Mr. Steve Benjamin, a technical manager from Carlisle Coatings & Waterproofing, Inc., to determine the weights of the waterproofing, drainage, and root protection membranes needed for green roof installation.

Our attention to detail and acquisition of proprietary information from industry enabled us to produce data that with a high level of accuracy.

Objective Two: Determine if the Buildings Could Support Green Roofs

The second objective we completed was to determine if either of the buildings could support green roofs. Each of these buildings was constructed about a half a century ago, and there was never any thought given to adding the weight a green roof has to the roofs of these structures. Additionally, building codes were less stringent 50 years ago than they are today, not requiring engineers to design the roofs to hold as much weight as today's standards do. In order to determine the ability of each of the buildings to support a green roof, we carried out a structural analysis for each.

Structural analyses determine the strength and rigidity of all types of structures. A structural analysis encompasses the properties of the system being analyzed, as well as a knowledge and application of loadings determined from codes and local specifications. For retrofits, such as this project, structural analyses are carried out on existing buildings. From these, a determination can then be made about whether structural modifications are required. Following our initial site visits to both the CDC garage and WCUW, we could see that the roofs were supported by trusses, so the proper method to follow was to conduct a truss analysis for each building. A truss analysis consists of calculating the stresses and forces in each truss member. We used this information to identify the trusses' critical members, those which would fail under the least amount of loading, and the load which can be placed on the truss can then be determined. In order to determine this, we observed and measured the size, placement, and orientation of each truss, as well as the materials used to construct the trusses, buildings, and roofs. In order to accurately carry out this procedure, we first had to gather this background information.

In order to complete the two structural analyses, we gathered background data about each of the buildings, the truss members, and design loads. We had to gather the following data about each building: the materials used to construct the building, trusses, and roofs, the dimensions of the buildings and trusses, the year the buildings were built, and the approximate weights of both the trusses and roof structures (see Figure 14). We also had to research the design loads required by building codes, such as snow loads, and any other live loads associated with green roofs.

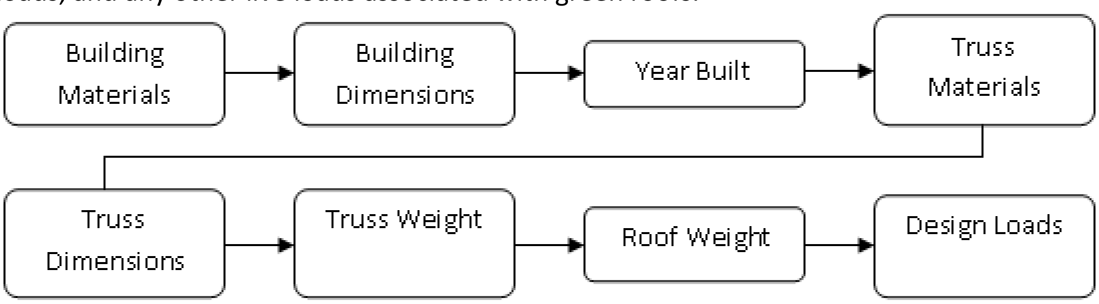

Figure 14: Data Needed

The first step in gathering the necessary background information was to determine the specifications of the buildings and the trusses. To accomplish this, we conducted site visits to the MSCDC's maintenance garage and the WCUW Radio building. We visually inspected each building, to determine the materials used during construction. We photographed each building and the condition of each roof. We also measured the dimensions of each roof, as well as the roofs' heights, and used this information to sketch layouts of each roof. We also attempted to find plans for each of the buildings. As another set of reference points, we contacted Mr. Steve Teasdale, the executive director of the MSCDC, and Larry Haley, an architect and board member at WCUW Radio, to find this data. Then we searched through the Worcester Assessor's Office's online property value database to determine what year the buildings were built, the block and lot numbers for each, and any design information they may have had. As another way to determine the approximate age of each building, we contacted the Worcester Department of Public Works Water Operations Division by phone. We inquired as to what year the water service was turned on to each lot. We also went to the Worcester Department of Inspectional Services, at 25 Meade St, to find the data there. We spoke with a building inspector about the buildings, and submitted a request for any documentation the city had pertaining to each building. Once we had this information, we proceeded to determine the specifications of the trusses.

The next step was to determine the specifications of each truss. This involved measuring their dimensions and orientation, and calculating their approximate weights. In order to calculate the capacities of the trusses, we needed to determine their dimensions, orientation, and materials. During our site visits to the CDC garage and to WCUW, we were able to obtain this data. We used a ladder to access one of the trusses at each building, and we took the dimensions of each truss member. We measured the length and cross section of each member with a standard tape measure. We also measured the spacing between members and photographed the orientation of the trusses within each member as well as the location of the trusses within the building. We then measured the distance between each truss. The final step we took in determining the truss's specifications was to examine the material used for each member. This allowed us to calculate the approximate weight of the truss, by multiplying the each member's cross sectional are by a weight found in a steel manual by the length of the member. We then added each member's weight and divided by the length of the truss to calculate the dead load of the truss. Once we had the specifications of each of the trusses, we then proceeded to calculate the weight of the roofing materials.

The next step was to determine the approximate weight of the roof decking. We did this by measuring the thickness of the steel decking with a micrometer. Once this was found, we consulted manuals to determine the approximate weight of the decking material, and any concrete placed on top. Standards from the American Society of Civil Engineers (ASCE), and the American Institute of Steel Construction (AISC) were consulted. We also researched industry catalogs from steel decking and roofing manufacturers. We used this data to develop a range of weights for the existing roofing material of the buildings.

The final step in gathering the background data was to research what design loads the buildings needed to adhere to at the time they were built. In order to find these loadings, we consulted the Massachusetts State Building Code 780 CMR 16.00, which pertains to structural design. This document contained the values for snow load, wind load, rain load, and other design loads the roofs need to carry, as well as associated live loads the structure must bear. We also consulted structural engineering textbooks and manuals from the American Society for Testing and Materials (ASTM), to determine the factors of safety and other factors involved in building construction. After gathering all the necessary loading data, we were able to proceed with our calculations.

There were several steps for carrying out the calculations for this objective. First, we constructed influence lines for each truss member. We determined the maximum allowable stress and force in each member, and calculated the maximum dead load that the trusses could each support before each member would fail. We then identified the critical members and dead loads and compared this against the weights of the structure and the design loads to determine the range of weights we could add to the structure before failure occurred.

The first step of the calculations was to construct influence lines for each member. However, before this, we needed to identify the truss as stable and statically determinate. To do this, we used the equation $r + b = 2j$, where r is the number of unknown reactions, b is the number of bars (members), and j is the number of joints in the truss. If the truss was found to be statically indeterminate, it must be looked at to determine what, if any, members could be ignored to satisfy the above equation. Once this was done, we constructed the influence lines, assuming that the loading force was vertical in the downward direction, from the top of the truss. The influence lines were constructed using a unit force of 1. Since the trusses are both symmetric about their centers, we only had to construct influence lines for one half of the truss, and then could flip the diagrams around the center axis for the remaining members. We first determined the influence line for the vertical reactions at the supports. This was done for one support by calculating the moment about the other support with a unit force on the truss at every joint along the top chord. We then summed the forces in the y-direction to find the reaction at the opposite support, and used the method of sections to move through the truss and determine the forces in each of the members. Simply summing forces in both the x- and y-directions for each cut was sufficient. In order to do this, simple geometry was used to calculate the x- and y-components of the diagonal members by multiplying by the cosine and sign of the angle between the diagonal and horizontal members, respectively.

To graph our results, we drew a diagram of the truss and drew horizontal axes beneath the diagram, and labeled them differently for each member. We took the critical loading points for each member and graphed them on the axes. The values of the influence lines for every member were zero at the supports. We then drew lines connecting the peaks and the ends of the diagram. The influence lines not only showed us how each member reacted to a unit force moving along the truss, but whether the members were in tension or compression as well. The step-by-step procedure for construction of influence lines can be seen below in Figure 15. After we constructed our influence lines, we were able to move on to determining the allowable stresses and forces in each member, and their associated maximum allowable dead loads.

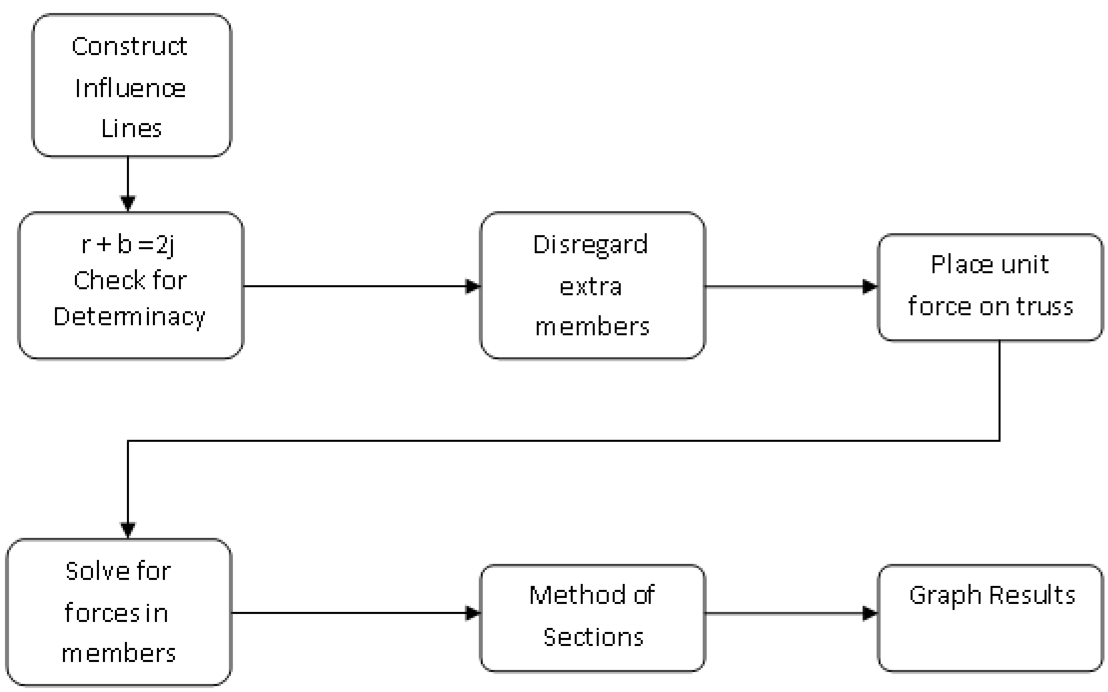

Figure 15: Procedure for constructing influence lines

Once we completed the influence lines, we moved on to determining the allowable stresses in each member. In order to move forward with this, we used the background information we gathered about the trusses. We needed to know the cross-sectional area for each member, its base and height, its length, and for the double angle members, the distances between the centroids of each rectangular area and the centroid for the entire member. The procedure we followed for determining allowable stress, force, and dead loads for each member can be seen below in Figure 16.

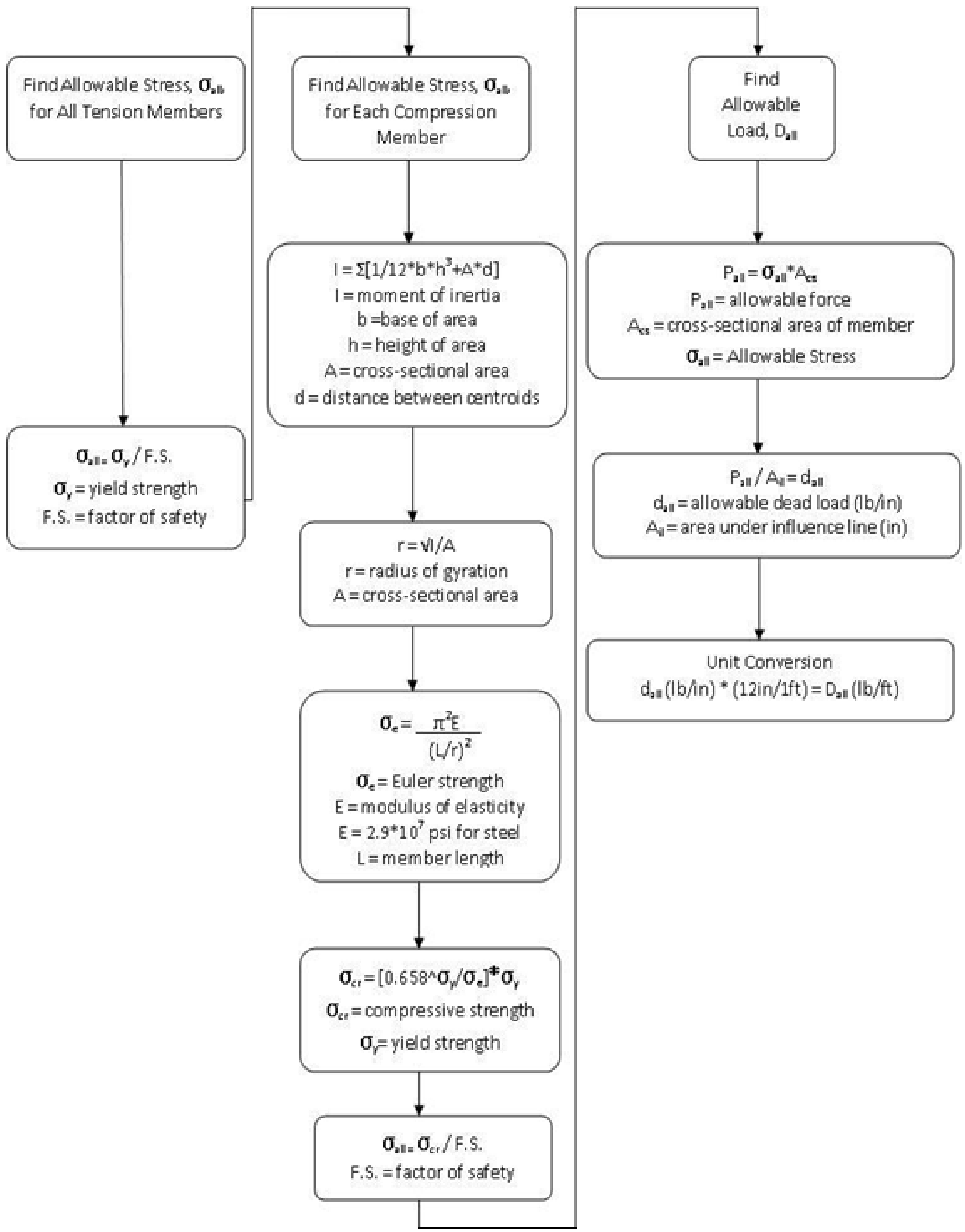

Figure 16: Procedure for calculating maximum allowable dead load

We then proceeded to identify which members were in tension and which were in compression. We reviewed the graphs of the influence lines, and if the net area under the curve was positive, the members were in tension. If the net area was negative, the members were in compression. Once we had identified which members were in tension and compression, we could begin to calculate the maximum allowable stress in each member.

Finding the maximum allowable stress is different for members in tension and members in compression. For tension members, we divided the yield strength of steel, σ_y, by the factor of safety. The values for these variables were found through consulting prior projects, referencing engineering texts, and speaking with a professor. The values we used were 35,000 psi for σ_y, and a factor of safety of 1.67. This calculation gave the maximum allowable stress for all tension members. For members in compression, the procedure is more complex. We carried out the following calculations for each member with differing geometry. We first calculated the moment of inertia, I, for each member. We took the sum of all the smaller moments of inertia for the double-angle members. We followed the formula: $I = \Sigma[1/12*b*h^3 + A*d]$, where b was the base dimension, h was the height, A was the area, and c was the distance between the centroid of the beam and the area being measured. After determining I, we proceeded to calculate the radius of gyration, r. We used the following equation, $r = \sqrt{I/A}$, where I is the moment of inertia of the member, and A is the total cross-sectional area. Once we found r, we then calculated the Euler strength of the members, σ_e, using the following formula: $\sigma_e = (\pi^2*E)/(L/r)^2$. E is the value for Young's Modulus of elasticity, which has a value of $2.9*10^7$ for steel, and L is the length of the member. After we found the Euler strength, we calculated the critical strength, σ_{cr}, of the members. We used the following equation, $\sigma_{cr} = (0.658^{\wedge}\sigma_y/\sigma_e)*\sigma_y$. Once the critical strength was found, we divided it by the factor of safety, 1.67, to determine the maximum allowable stress in the members. Once we determined the maximum allowable stresses in each of the members, we proceeded to determine the maximum allowable forces in each.

Once we had found the maximum allowable stresses in each of the members, we proceeded to determine the maximum allowable load, P_{all}, in each member, as well as the maximum allowable dead load on the truss for each member, D_{all}. To find P_{all}, we used the following equation: $P_{all} = \sigma_{all}*A$. Once we found the allowable force, we used the following equation to find the maximum allowable dead load that could be placed on the truss for each member: $D_{all} = (P_{all}/A_{IL})$, where A_{IL} is the net area under the influence lines for each member. The final results of our calculations determined D_{all} for each member in lb/ft. We then reviewed our findings in a spreadsheet and determined the critical members by identifying those with the lowest D_{all} values.

After we identified the maximum allowable dead load that could be placed on each truss, we then calculated the weight of the existing roofing structure. We began by calculating the weight of the truss itself. To do this, we carried out the following calculations. We found the weight of each member using the equation W = A*L*3.404, where A is the cross-sectional area, L is the length, and 3.404 is a value found in our research for the unit weight of steel. We then divided W by 12 to calculate the truss' dead loads in lb/ft. We then took the values we found for the weight of steel decking and multiplied by 8 ft, the width of the area of roof supported by each truss, to find the dead load of the roofing materials in lb/ft. We also accounted for the snow loads and live loads found from the building code and building inspector, and multiplied those by 8 ft as well. After we had determined the dead load of the trusses, roofing materials, and design loads in lb/ft, we added them and subtracted their sum from the maximum allowable dead load found earlier to determine the range of weights our green roofs could be. If the weights of the green roofs exceeded this window, the roof would be in danger of failure and collapse.

To verify our calculations we used ANSYS software. ANSYS is a structural engineering program with various uses. We drew each truss in the program and input information for each member such as its length, cross-sectional area, and modulus of elasticity ($2.9*10^7$psi). We choose to treat the system as a two dimensional system with each member defined as a link. This way the program only considers axial loads which, for the purpose of our project, was the best option. Based on our calculated design load we found the weight per inch spanning the truss by multiplying the design load by the distance between trusses. Then we were able to add a point load at each joint on the top of the trusses under the assumption that the weight was an equally distributed load. At that point we ran the program which generated the vertical deflection at each member and axial stress. Since we had already calculated the allowable stress in each member we were able to compare the allowable with the projected stresses and see what members could be insufficient for the added load.

To further provide a check on our calculations, we set up an interview with Professor Leonard Albano of WPI's Civil & Environmental Engineering Department. We presented our findings to Professor Albano to seek his opinion on whether we had correctly carried out the procedures and arrived at a reasonable conclusion.

The structural analysis was a critical objective that needed to be fulfilled because it set the limitations for what the green roof designs could be, as well as identified if any structural modifications needed to be made to allow for green roof construction. Most importantly, it ensured that the buildings are safe for people to use if green roofs are installed.

Objective Three: Research Green Roof Design Options

Once we had successfully identified what loads the buildings were capable of supporting we built off *Objective One* with more specifics of design. The next objective was to research green roof design criteria. Before we were able to meet this objective, we did some in-depth research on green roofs- their various purposes and types. This objective helped us to achieve our goal by understanding the characteristics that were important for buildings to have in order to support a green roof. The process involved researching various types of green roofs and researching what they were best suited for, keeping in mind the intended use of the roofs, the environmental factors that affect the region, the Commonwealth of Massachusetts' regulations, and the structural capacities of the buildings from *Objective One*. From our interviews we knew that these design options had to be practical and economical, and also had to meet the desires of the building owners and the MSCDC.

First, we identified the possible purposes that these roofs could have served. We researched the possibilities for them to be used to increase the energy efficiency of the buildings, to be used as demonstration sites for the community, or to be used as community food gardens. To identify other potential uses we researched green roofs on online journals and past studies. After we established a range of options, we interviewed our liaison, Peggy Middaugh, and Larry Haley, a board member from WCUW Radio, to determine the sponsors' potential uses for green roofs. Determining the potential uses of the roofs was an important step because it helped us determine what types of green roof systems and components to further investigate.

The next step we took was to research different green roof systems. We contacted Mr. Chase Terrio, a project manager from Suffolk Construction, who worked on the John W. McCormack Federal Building in Boston. Mr. Terrio was able to provide us with information about both extensive and intensive green roofs as well as modular and traditional green roofs. We also contacted Mr. Markham and Ms. Bezanson from Weston Solutions, who were able to provide us with a great deal of information about their product. We also researched online for different green roof systems. We contacted Mr. Brackney from Apex Green Roofs for information about his company's mat system.

We then researched different types of green roof plantings. We reviewed literature from past projects, journals, and magazines to get an idea of what had been used in the past. Additionally, we set up interviews with green roof professionals. We interviewed Ms. Lynne Deninger, an architect from Cannon Design who worked on WPI's East Hall green roof, to get an idea of how to select the types of plants to use on the roofs, and which plants may be better suited to our needs than others. We also conducted an interview with Ms. Casey Burns from the REC to determine if small crops were suitable plant material to use in some of the design options. Ms. Burns was able to provide us with insight into what types of plants Youth GROW cultivates and if there is any interest from the REC in using green roofs as gardens for growing food.

In order to get a better understanding of what a modular green roof looks like once installed, we conducted a site visit to WPI's East Hall. A portion of East Hall is covered by GreenGrid© modular trays from Weston Solutions. In addition to viewing an installed green roof, we looked further at the makeup of the soils and plants while there. We also identified phosphate runoff as a potential harmful effect of having green roofs installed.

Our sponsor raised the issue of green roofs and phosphate runoff. In order to get a better understanding of why phosphate runoff could potentially become a problem if green roofs were installed, we conducted some background research online. We also decided to set up an interview with Professor Suzanne LePage of WPI's Civil & Environmental Engineering Department. Professor LePage has conducted research on green roofs and phosphate runoff using WPI's East Hall. We also asked Professor LePage about ways to minimize or mitigate the phosphate runoff green roofs produce. She provided us with some common methods to harvest or filter the runoff water from green roofs as ways to accomplish this.

The designs' loadings and costs were the final items that we used to eliminate unfeasible options in the design process. We determined the weight of each design and compared it to the capacities identified in the *Objective One*. We used the knowledge gleaned from this objective to quantify data found in *Objective One: Determine Load Requirements for Green Roofs*, and *Objective Four: Provide Cost Analysis.*

Objective Four: Provide Cost Analysis

Providing an accurate and thorough cost analysis was critical for determining the feasibility of implementing green roofs in the Main South Community. Upon completion of our project, the MSCDC will be sending the result to potential sponsors for funding. So, for each design option it was necessary to provide a complete cost analysis so that funders will know how much money is needed and what it will be used for. First we established all the potential contributors of the direct cost when installing a green roof on an existing building (see Figure 17). Then we looked at the results of *Objective One* and Objective *Two* and the cost benefits associated with each design.

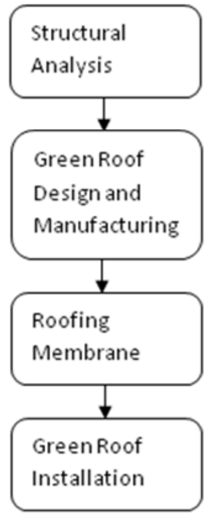

Figure 17: Direct Cost Contributors

The first essential piece of information needed to calculate the direct cost is based on the structural analysis. Before any green roof can actually be installed a professional structural engineer would need to be hired to complete an analysis and conclude that the structure can support the added weight. We contacted a structural engineer who provided us with a rough estimate of a commercial building about 140' by 50'. If it is found that the structure cannot support the weight then we assumed that the project will shift to another site that is capable of bearing the load without modifications. Construction of modifications is time consuming, not environmentally friendly, and expensive so for the purposes of our project we did not consider this price.

The price of the green roof material was the most significant cost factor. Green roof companies design and manufacture the plants and soils, and then deliver the material for one combined price. This combined price is usually given as a price per square foot. We located this cost by conducting a phone interview with an employee of Weston Solutions who manufactured the only green roof currently in Worcester. Based on this we found the estimated price per square foot of the material for several green roof systems. Next, we needed to find the price of installation. Since installation is something that is typically subcontracted to roofing and/or landscaping companies, we contacted a roofer with experience in green roof installation and received a rough estimate per square foot for each green roof system. This information allows funding flexibility and provides funders the essential information to make an informed decision as to which design option to install.

In addition to the price of installing green roofs, our sponsor requested that we provide a cost estimate for green roof removal. Although this is not a common task, we interviewed a superintendent who had experience removing a intensive green roof. From his experience we were able to formulate an estimate of the relationship between costs of installing and uninstalling several green roof systems. This information will be useful for property owners and funders if the building owners are not satisfied with the decision to install a green roof and would like to have it removed.

Additionally we provided the cost of single ply roofing installation so that interested parties can compare the two costs. Since we were focused on existing buildings, we assumed that the roofing material needs to be replaced. We contacted a roofer who provided us with a basic cost per square foot of a simple single ply roofing membrane that is typically placed on a flat roof of a commercial building. We also found the lifetime of the membrane with and without green roof protection so that we could generate a chart of installation costs in the future. This information will show some of the financial benefits of green roofs and is crucial to motivate sponsors and prove that the project is helping to provide sustainability and green infrastructure.

After gaining the necessary information we submitted a conclusive cost analysis including costs and savings associated with several green roof systems. The report will inform funders of approximately how much money will be needed for each aspect of the project, where the money will be going, and the resulting financial benefits moving forward. The information will justify the project financially and directly link the project to the goals of the MSCDC which are to implement green infrastructure in the Main South Community.

Summary

Through completing our objectives, we achieved our project goal. As the project progressed, we changed our objectives to better allow us to achieve our goal. The results we found were compiled into a final deliverable. This was a concise paper which presented green roofs in an informative fashion intended for property owners for further research. Community members looking to improve the quality of life in Main South and set an example toward a greener and more sustainable future will see it as an innovative and exciting project worth contributing to.

Findings

Introduction

The following section outlines the results of our data collection and research. It includes information on the support requirements of a green roof, the strength of a structure that can hold a green roof, the cost of a green roof, and further site identification. These areas build upon each other to create a data base from which further research can be conducted.

We found that the initial two buildings identified by the MSCDC were not structurally capable of supporting the weight of themselves, a basic green roof and the snow load without making modifications to strengthen their existing structures. The capital that would be spent on making these modifications could be better spent on other sites, and so the decision was made to identify other possibilities for the MSCDC, and other developers, to explore.

After conducting the structural analyses of the roofs located on the MSCDC's garage and the WCUW's building, we came to the conclusion that they were not structurally capable of supporting the expected additional loadings associated with green roofs. As a result of this, we created a new objective: to identify other possible locations in Main South for further investigation into green roof installation.[1]

Support Requirements for Green Roofs

The lightest extensive green roofs can have a saturated weight of at least 11 lbs. per sq. ft. (psf) in addition to traditional roofing dead loads. While the most intensive green roofs can have a weight of over 80 psf.

A basic extensive roof which weighs 18-34 psf when saturated, while GreenGrid©'s 2.5-inches-deep modular system weighs 11-13 psf and its 4-inches-deep system weighs 18-22 psf. These could be realistic weights to design a roof structure around.

We found that the typical basic intensive roof can weigh upwards of 80 psf when fully saturated. This includes the weights of the waterproof membrane, insulation, drainage layer, filter fabric/root barrier, and growth medium with the plants. Another, lighter format of the intensive roof involves the use of modules.

The GreenGrid© modular intensive system developed by Weston Solutions is far lighter than the typical basic intensive roof and weighs 36-44 psf when saturated. These modules are 8-inches in depth and can be placed directly upon the basic waterproofing and insulation layers, which have a total weight of approximately 0.6 psf.

We found that one can design a roof to hold a green roof with an additional deal load to the structure as low as 11 psf and as high as 80+ psf. These weight ranges and those between are shown in Table 6. We believe that the best green roofing option for the main south community would be roofs in the 20 psf range and that this weight is what should be designed for.

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[1] For new objective, see Findings: Additional Sites

Table 6: Weight of Green Roofs

Green Roof System	Weight (per sq. ft.)
Modular GreenGrid 2.5”	11-13
Modular GreenGrid 4”	18-22
Basic Extensive	18-34
Modular GreenGrid 8”	36-44
Basic Intensive	80+

Green Roofs not Feasible for Either of Our Buildings

The installation of green roofs to both the MSCDC’s garage and the WCUW Radio building is not feasible. Through our research, we have found that neither building would be able to support the additional weight of a green roof without structural failure.

The members in each building’s trusses able to support the lowest corresponding dead loads dictated the capacity. The results of these calculations are summarized in Table 7 and Table 8 and our full calculations can be seen in *Appendix B*. *Appendix B* shows the specifications of the truss’s members, their structural properties, and the results of our calculations, which show the maximum allowable stresses, forces, and dead loads for each member. As can be seen from Table 7, members BP and NBB in the CDC’s garage trusses are the critical members. These members have a maximum allowable load of 391.57 lb/ft on the truss, or 49 psf distributed across the roof. Table 8 shows the critical members for the WCUW building, members BP and NBB. We found these members to have a much lower maximum allowable load, 181.40 lb/ft across the truss, or 22.7 psf when distributed across the roof.

The dead load of the CDC’s garage’s current roof structure is 14.48 psf. A breakdown of the separate components and their associated weights can be found in Table 6. We found the weight of the truss to be 35.84 lbs./ft, or 4.48 psf. The weight of the roofing membranes and decking was 10 psf. The modern snow load required by Massachusetts state building code is 55 psf. The minimum weight for a green roof is 11 psf. This produces a design load of 80.5 psf. This load exceeds the current structural capacity of 49 psf for the building.

Table 7: Summary of loads for MSCDC Garage

MSCDC Garage	
Critical Members	BP & NBB
Critical Dead Load (lb/ft)	391.57
Critical Dead Load (psf)	48.94625
Truss Weight (lb/ft)	35.84
Truss Weight (psf)	4.48
Roof Weight (psf)	10
Green Roof Load (psf)	11
Snow Load (psf)	55
Design Load (psf)	80.48

ANSYS software verified our finding. Figure 18 shows the stresses in each member with positive numbers being in tension and negative numbers in compression. These numbers verified that the truss could not support the added weight. The generated axial stress exceeding our calculated allowable stress in 32 of the 53 members (see Appendix B). It also shows a maximum deflection of 4.506 inches which is not acceptable in a truss of that size.

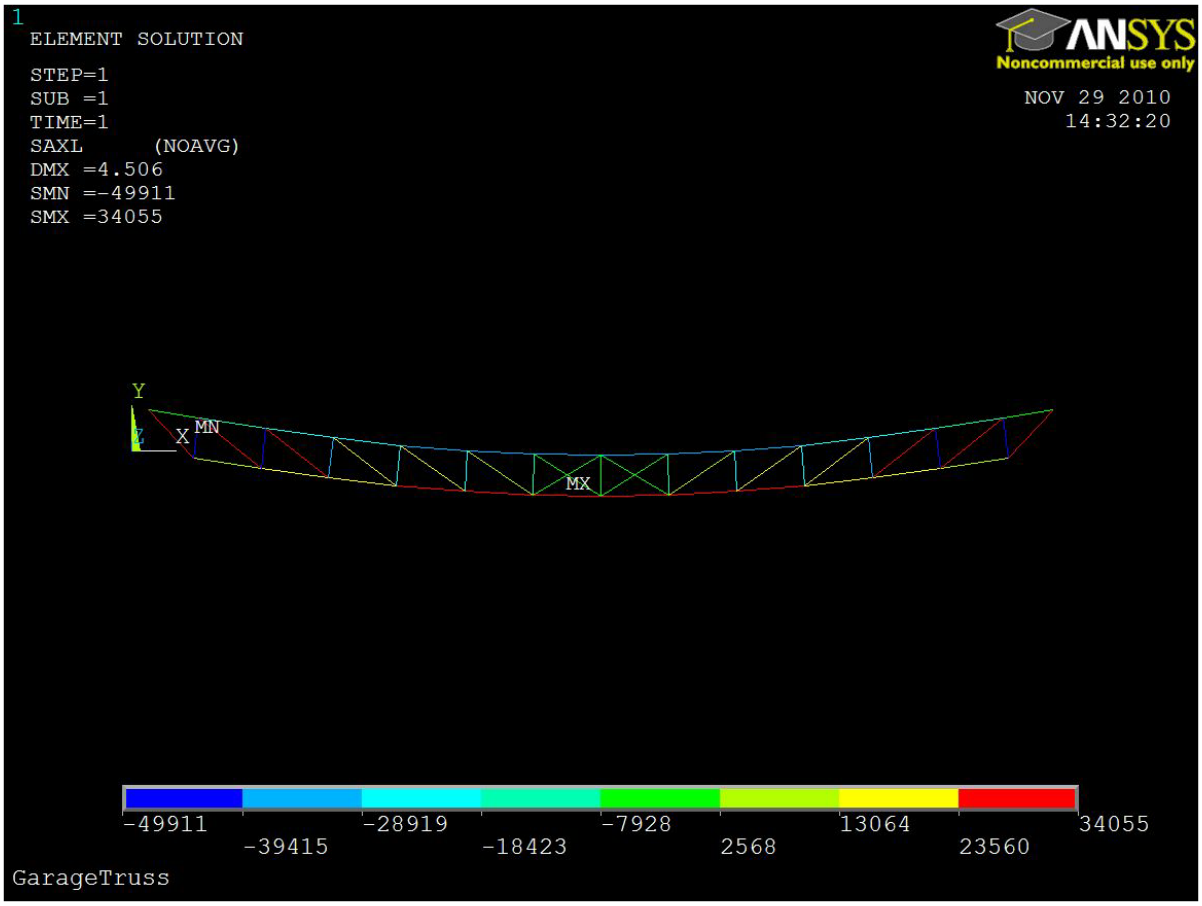

Figure 18: ANSYS Computer Model of MSCDC Garage Truss

The dead load of WCUW's roof structure is 12 psf and a breakdown of the separate components and their associated weights can be found in Table 8. The allowable dead load for the WCUW structure is 22.7 psf. We added the modern snow load required by Massachusetts state building code of 55 psf to obtain a total dead load of 35.45 psf. The minimum load for a green roof is 11 psf. The new design load would then be 46.45 psf. This load exceeds the current structural capacity of 22.7 psf that the trusses can support.

Table 8: Summary of loads for WCUW Building

WCUW Radio	
Critical Members	BP & NBB
Critical Dead Load (lb/ft)	181.4
Truss Weight (lb/ft)	22.08
Truss Weight (psf)	2.76
Roof Weight (psf)	10
Critical Load (psf)	22.675
Green Roof Load (psf)	11
Snow Load (psf)	55
Design Load (psf)	78.76

Again, ANSYS verified our finding. Figure 19 shows the stresses in each member with positive numbers being in tension and negative numbers in compression. These numbers verified that the truss could not support the added weight. The generated axial stress exceeding our calculated allowable stress in 34 of the 55 members (see Appendix B). It also shows a maximum deflection of 3.328 inches which is not acceptable in a truss of that size.

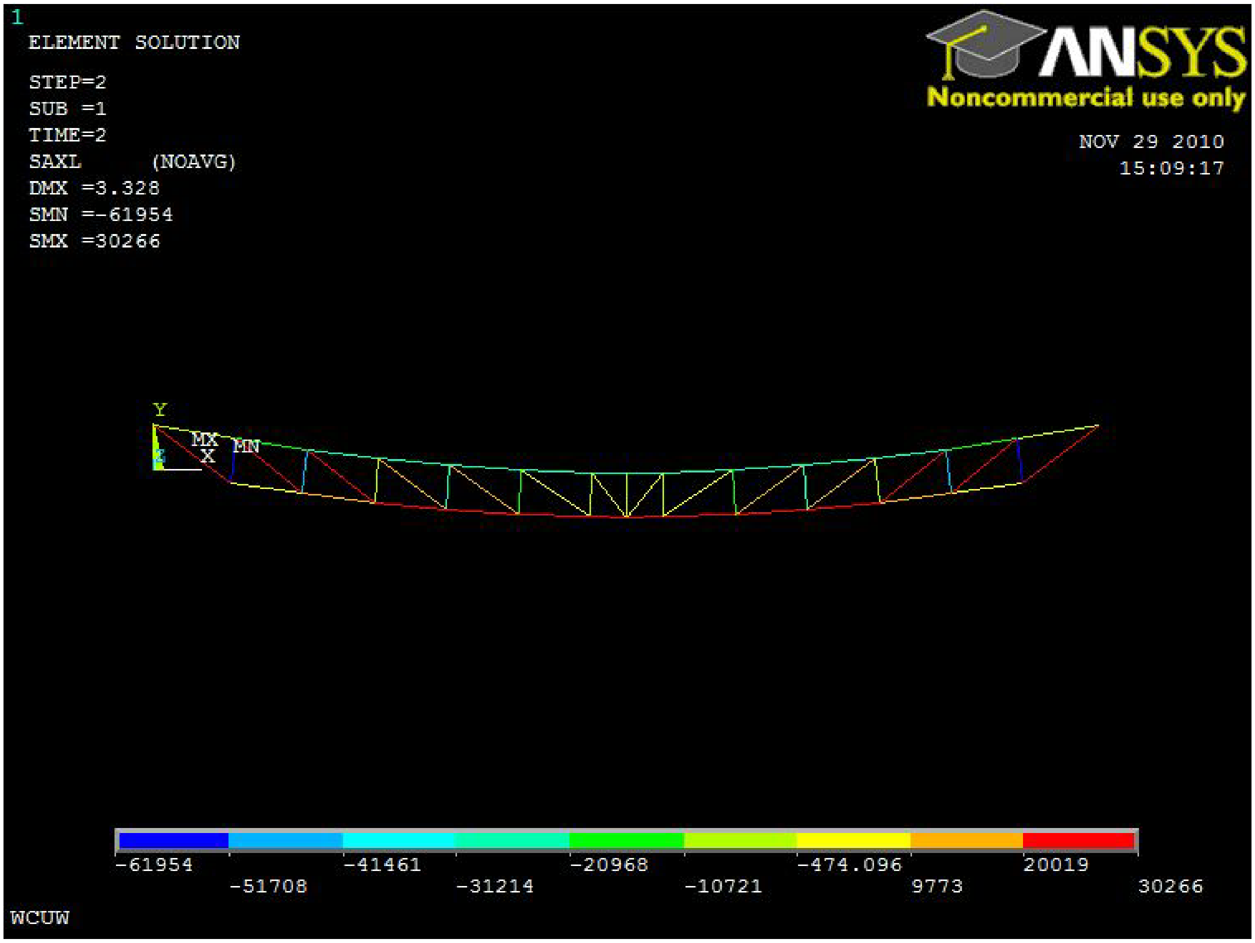

Figure 19: ANSYS Computer Model of WCUW Radio Truss

Our meeting with Professor Albano confirmed our initial findings. After reviewing our findings and our methods and calculations, Professor Albano concurred with our finding that the buildings would not be able to support the addition of green roofs.

Cost

Upon completion of our tasks we were able to formulate a cost estimate of a green roof in the Main South community. The price is not meant to be a precise number, but to provide funders and building owners with a basic cost estimate. In Table 9, this cost estimate is separated into each of the components of the direct cost, and then calculated from there. We also provided a cost estimate of a conventional roof so that funders will have a cost to compare it too.

Table 9: Cost Breakdown

Job	4" Modular	8" Modular	6" Traditional
Structural Engineer	$10,000-$20,000	$10,000-$20,000	$10,000-$20,000
Green Roof Design and Manufacturing	$11-15/sq ft	$18-23/sq ft	$7-9 /sq ft
Roofing Membrane	$5-7/sq ft	$5-7 /sq ft	$5-7/sq ft
Green Roof Installation	$7-9 /sq ft	$8-10 / sq ft	$11-13/sq ft
Total Without Modifications /sq ft	$23-$31/sq ft	$31-$40 /sq ft	$23-29 /sq ft

Note: Roofing Membrane and Green Roof Installation should be one inclusive bid.

Example 1) 4" Modular Extensive green roof on 10,000 sq ft building without need for modifications:

Minimum cost: 10,000+(23)*10,000= $240,000

Maximum cost: 20,000+(31)*10,000= $330,000

The final price will be between $240,000 and $330,000.

Example 2) 6" Traditional Intensive green roof on 10,000 sq ft building without need for modifications:

Minimum cost: 10,000+(23)*10,000= $250,000

Maximum cost: 20,000+(29)*10,000= $310,000

The final price will be between $250,000 and $320,000.

The cost of a structural engineer was estimated to be between $10,000 and $20,000. This was based on an estimate given to us from a structural engineer of $15,000. However, the $15,000 price was based on a three story building that is about 7,500 square feet. Since there are many variables involved with this cost estimate we assumed a price range of about $10,000 to $20,000. Some of the factors that could affect this price include the availability of building plans, the complexity of the building, the susceptibility of snow drift on the rooftop, and many more. These factors make the structural analysis difficult to estimate without a specific site, but we have concluded that the price will most likely be within our given range.

The costs of green roof design and manufacturing was based on prices provided for us from Weston Solutions and other industry professionals. Both modular prices are based on a cost sheet we received from Weston Solutions who designed and manufactured the modular green roof on top WPI's East Hall. The price was $11-$15 per square foot for the 4" deep modules with the 8" modules at a $7-$8 premium. The price varies depending on the area to be installed. The greater the area of the green roof, the lower the cost per square foot is going to be. For this price the manufacturer will design the soil, plant the plants in a nursery for about four to six months, and deliver the trays to the site. An traditional intensive green roof would cost about $7-$9 per square foot. This is cheaper since the plants are not planted until installation and the soil can be transported in bulk, as oppose to in modular trays.

The cost of a single ply roofing membrane that is typically placed under green roofs is about $5-$7 per square foot. Since we only considered existing buildings we assumed that the membrane needs to be replaced. Placing a green roof on top of an existing roofing membrane is not recommended because it would void any roofing warranty and also require a labor intensive process to replace the roofing membrane once a green roof is installed. The roofing material will also last about twice as long with a green roof than without due to the UV protection that the plants and soils provide. So, replacing the membrane at the same time as the green roof is a smarter investment for the building owner. Figure 20 shows the average cost of all four options over 25 years since that is when the conventional roof will need to be replaced if no green roof is installed. It is important to consider because while $300,000 looks like a large initial cost, the roofing membrane is about $60,000 which would need to be done regardless. Also, since green roofs can double the lifetime of the roof the owner is saving the $60,000 that it would cost to replace it. So in that regards, the owner can consider $120,000 of the cost to be inevitable.

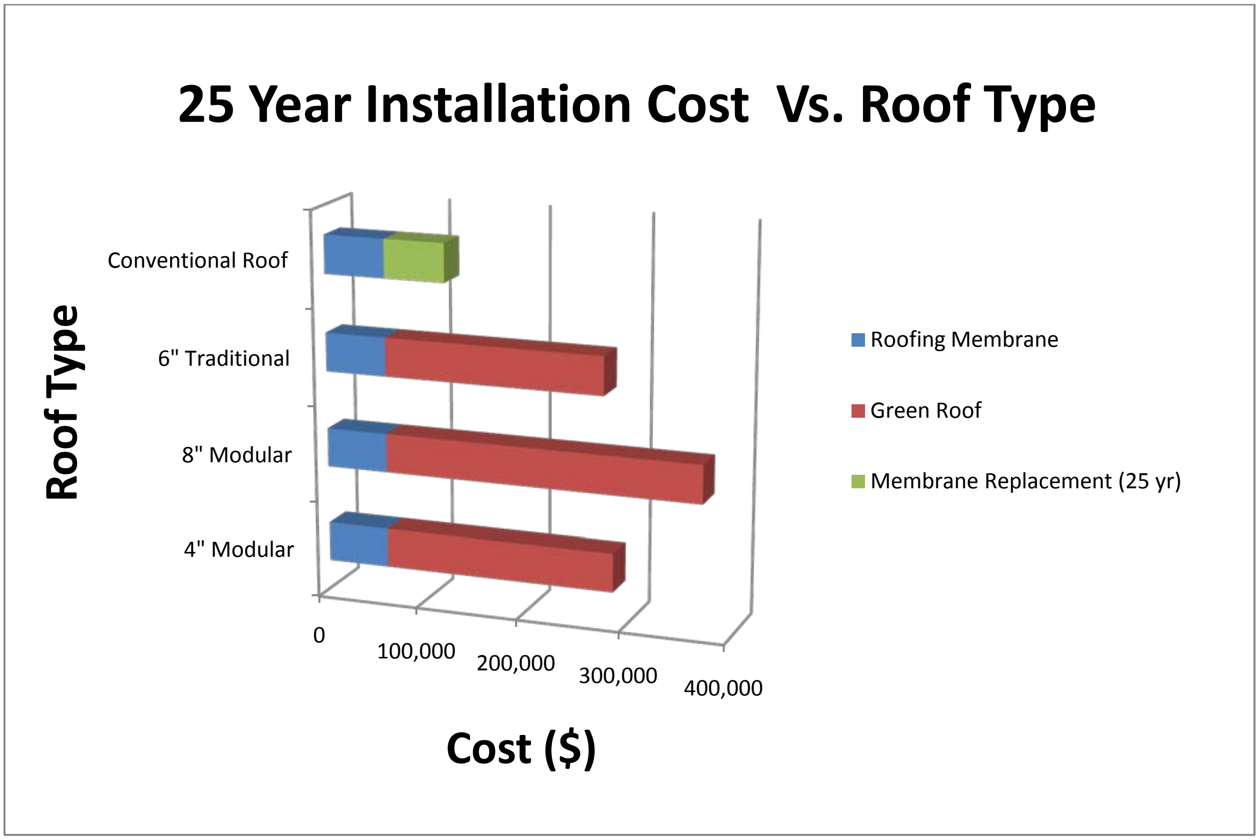

Figure 20: 25 year Installation Cost vs. Roof Type

The cost of the green roof installation was based on our conversations with roofers and superintendents with experience installing green roofs. The cost for the 4" modules was the cheapest to install at $7-$9 per square foot. This is because installation consists of laying out a drainage mat and any other materials necessary and then simply placing the modules in place. The 8" modules are a dollar more per square foot due to the added volume and weight. Traditional intensive systems are more expensive to install at $11-$13 per square foot. They are more expensive because installation requires more protection between the roofing membranes and also includes all of the planting.

We recommend that only one contractor be hired to install a new roof membrane and a green roof. One inclusive bid will be substantially lower than bidding two separate jobs. This way there will be competitive bids which will include a new roofing membrane, green roof installation, and any permits or excess expenses.

If, for any reason, the building owner would like to uninstall the green roof, it is possible, however expensive. Modular systems are much easier to uninstall since the trays can be easily removed. The cost of uninstalling a modular system would be about the same as installing it, since the process is the same. For traditional intensive roofs, uninstalling would be a labor intensive, expensive process. In our interview with Mr. Chase Terrio he explained a scenario on the McCormack Building in Boston which he was involved with and the drainage mat was placed upside down. They needed to then remove all the soil in order to flip it over correctly. He explained that a crane and six men loaded 150 cubic yards of soil onto the roof in two hours. In order to remove all of this soil 12 men were hired to hand shovel the dirt which ended out being a three week process and obviously very costly. So, uninstalling a traditional green roof can cost as much as five times the cost of installation.

Additional Sites

[2]*We progressed by identifying possible future green roof sites within the Main South Community using aerial photographs and by conducting site visits. We then deemed it necessary to narrow our search. We developed a set of criteria to identify specific areas and buildings to investigate further.*

The system used to identify these buildings took into account the capacities of the combined sewer system in the area (see Figure 21), and the estimated structural capacities of the buildings based upon their intended uses and common construction practices when they were built. It also took into account the interest involved in the potential for further study and cooperation with the MSCDC. In addition, we accounted for the visibility of the roofs in order to choose sites that community members could be aware of, which may inspire further participation in green technologies.

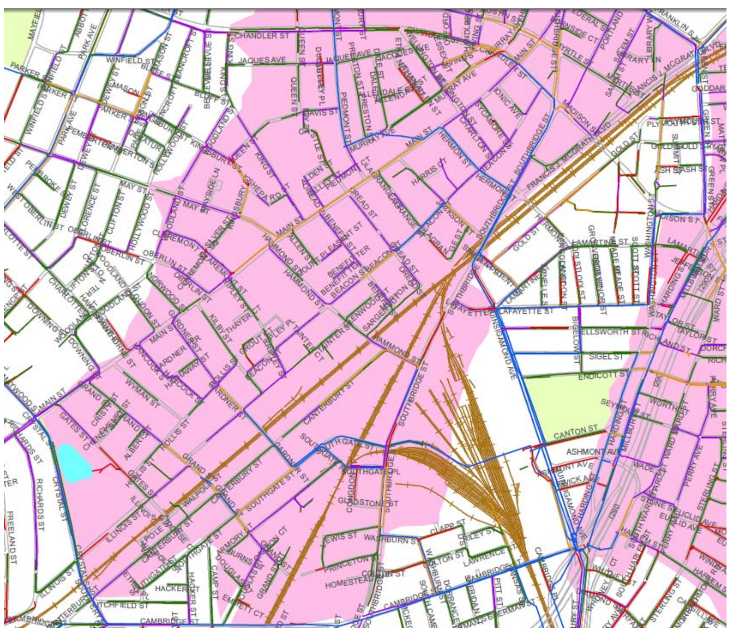

Figure 21: Area of Combined Sewer System (Shown in Pink)

We used a ranking system in order to quantify the potential for green roofs for individual buildings. The system (see Table 10) ranked building according to their structure, visibility, pipe size, roof area, and interest.

[2] Since the original buildings were found to be not feasible, this section explains the added objective of finding additional sites.

Table 10: Ranking System

Rank	Structural	Visibility	Pipe Size	Roof Area	Interest
0				0-4999	
1	Wood Residential	Not visible	30"	5000-6999	Low
2	Wood Commercial	Poorly Visible	20"-28"	7000-9999	Neutral
3	Masonry Residential	Moderately Visible	13"18"	10000+	High
4	Masonry Commercial	Highly Visible	9"-12"		
5	Brick Residential		8"		
6	Brick Commercial				
7	Steel Residential				
8	Steel Commercial				

We set up the rankings so that the structural properties of each building were twice as important as the roofs' visibilities. The roof area was looked at because larger roofs have the ability to host larger green roofs, which are able to sequester more rainfall and have a larger impact in storm water management. We made the importance of the sizes of the sewer pipes slightly above that of the visibility. The size of the sewer pipes is important, because it determines how much storm water (and sewage) can be collected. Smaller pipe sizes could more easily by overwhelmed during prolonged periods of rainfall and so it would be more useful to place green roofs in the areas serviced by these pipes. We then left the interest rank open to be more subjective with no numerical value. We did this because the willingness of building owners and tenants to participate in such a project has a very large impact, and without speaking to each owner and tenant individually, we found it more productive to leave this ranking subjective. We also did not include the cost of green roofs as a factor because we could not provide proper estimates for structural modifications, and because further investigation and overall feasibility is not greatly affected if there is no budget.

We established that there are approximately 160 buildings in Main South that have flat roofs and fall within the confines of the combined sewer system. These sites are shown in Figure 22. In Figure 22, the pink outline is the border of Main South, and the blue outline shows the areas which are part of the combined sewer system. We calculated this area to be approximately 450 acres. The green boxes with red outlines represent all the buildings with flat roofs we identified using aerial photography. We calculated that the combined area of all of these roofs covers is approximately 50 acres. These calculations can be found in *Appendix C: Area Calculations*. Because there are so many flat roof buildings that cover such a large area in Main South, we believe that investigating further for green roof feasibility should not be abandoned.

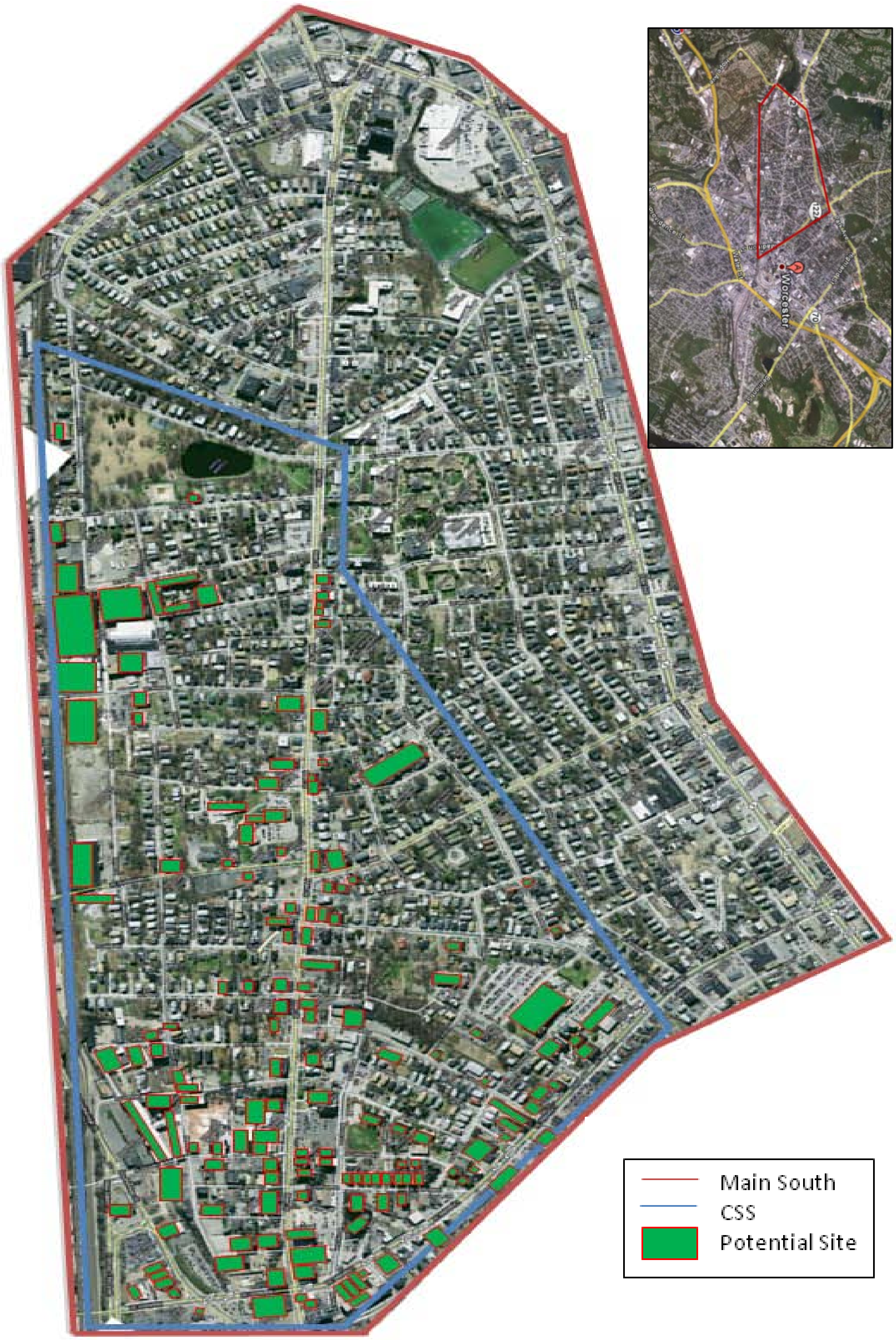

Figure 22: Possible Future Sites (in green) within Main South's CSS.

From these 160 sites, we have identified 58 as having the best potential for green roof installation. These 58 sites and their associated ranking are summarized in *Table 11*. From these sites we ranked the top buildings, of which the totals were highlighted in green. We also established that the locations whose 'interest' cell highlighted in green would be most likely to work on such a project. Additionally, the costs highlighted in green are the least expensive over all.

We calculated the range of costs presented in Table 11 so as to provide an estimate of the cost of installing a green roof at each location. This was calculated based on the square-footage of the roofs, and the estimated generic cost of a green roof and a structural engineer (\$10,000-\$20,000), as shown below:

Low Cost = \$10,000 + \$23/sf X Roof Area (sf)

High Cost = \$20,000 + \$31/sf X Roof Area (sf)

These results are intended to provide a list of sites having the most potential for the installation of green roofs. This list can then be used as a guide for further investigation into green roof feasibility in the Main South community.

Table 11: Ranking Results

Rank	Address	Owner	Structure	Visibility	Pipe Size	Roof Area	Interest	Total	Low Cost	High Cost
1	65 Tainter	The Boys & Girls Club	6	6	3	3	High	18	$734,500.00	$996,500.00
2	12 Queen	UMass Medical Center	6	5	4	3	High	18	$417,100.00	$568,700.00
3	26 Queen	UMass Medical Center	6	5	4	3	High	18	$525,200.00	$714,400.00
4	33,39,43 Hammond	New Method Plating & Enameling	6	5	4	3	Neutral	18	$613,796.00	$833,812.00
5	44 Hammond	Nettle LLC	6	5	4	3	Neutral	18	$1,059,950.00	$1,435,150.00
6	93 Grand	Main South CDC	6	6	2	3	Neutral	17	$977,150.00	$1,323,550.00
7	662 Main	MGM Pena LLC	6	5	3	3	Neutral	17	$1,241,236.00	$1,679,492.00
8	857 Main	Roman Catholic Bishop of Worcester	6	5	3	3	High	17	$508,525.00	$691,925.00
9	888 Main	Arthur Mooradian, Trustee	4	5	4	3	Low	16	$345,823.00	$472,631.00
10	689 Main	Sondatt B Prashad, Trustee	6	5	3	2	Neutral	16	$171,000.00	$237,000.00
11	95 Grand	Worcester EOEND	6	5	2	3	Low	16	$956,450.00	$1,295,650.00
12	653 Main	Hadley Apartments LLC	5	5	3	3	Neutral	16	$297,500.00	$407,500.00
13	45 Grand	Crystal Park Ltd Partnership	5	5	3	3	Neutral	16	$1,398,004.00	$1,890,788.00
14	49 Gardner	South Garden Realty Inc	7	6	2	1	Neutral	16	$149,564.00	$208,108.00
15	674 Main	Worcester Lofts Limited Partnership	6	5	3	1	Neutral	15	$134,200.00	$187,400.00
16	701 Main	PIP Foundation Inc	5	5	3	2	Low	15	$185,950.00	$257,150.00
17	845 Main	J & M Batista Family Limited	7	5	3	0	Low	15	$52,366.00	$77,102.00
18	875 Main	Clark University Trustees	4	6	3	2	High	15	$235,216.00	$323,552.00
19	19 Ripley	Crozier Inc.	6	2	4	3	High	15	$319,350.00	$436,950.00
20	64 Beacon	Vaios Theodorakos, Trustee	6	2	3	3	Low	14	$1,372,750.00	$1,856,750.00
21	98 Beacon	Steven M Rothschild, Trustee	5	2	5	2	Neutral	14	$173,875.00	$240,875.00
22	18 Hammond	Idak Convalescent Centers Inc.	5	5	4	0	Neutral	14	$84,865.00	$120,905.00
23	35 Lagrange	Joseph M & Stephen A Krosoczka	7	2	5	0	High	14	$119,250.00	$167,250.00
24	47 Lagrange	Sem Tec Inc	4	2	5	3	High	14	$311,185.00	$425,945.00
25	50 Lagrange	Joseph M & Stephen A Krosoczka	6	2	5	1	High	14	$135,580.00	$189,260.00
26	698 Main	Ediberto Santiago	5	5	3	1	Neutral	14	$154,900.00	$215,300.00
27	891 Main	Raymond A. & Judith Levine	6	5	3	0	Neutral	14	$81,369.00	$116,193.00
28	712 Main	Wellington Company	5	5	3	1	Neutral	14	$168,700.00	$233,900.00
29	945 Main	Clark University Trustees	4	5	3	2	High	14	$230,800.00	$317,600.00
30	14 Gardner	Lisa D Servant	5	5	3	0	Neutral	13	$84,060.00	$119,820.00
31	12 Hammond	Alfred Roy and Sons Inc.	5	5	3	0	Neutral	13	$28,216.00	$44,552.00
32	68 Gardner	68 Gardner LLC	4	5	1	3	Neutral	13	$1,409,320.00	$1,906,040.00
33	24 Kilby	Main South CDC	3	5	4	1	High	13	$148,000.00	$206,000.00
34	650 Main	Anastasios Karamanos	4	5	3	1	Neutral	13	$126,081.00	$176,457.00
35	660 Main	Community Renewal, Inc	3	5	3	2	Neutral	13	$171,345.00	$237,465.00
36	667 Main	General Realty Corp	3	5	3	2	Neutral	13	$205,500.00	$283,500.00
37	709 Main	Julio Romero	4	5	3	1	Neutral	13	$149,840.00	$208,480.00
38	720 Main	Chestnut Renewal Cooperation	5	5	3	0	Neutral	13	$93,950.00	$133,150.00
39	895 Main	Gordon J Turpin	5	5	3	0	High	13	$77,068.00	$110,396.00
40	108 Beacon	HW Beacon LLC	5	2	5	0	Neutral	12	$110,050.00	$154,850.00
41	22 Ethan Allen	Wellington Company	5	0	5	2	Neutral	12	$206,650.00	$285,050.00
42	868 Main	Quek Kevin Ying Xuan	3	5	3	1	Neutral	12	$162,720.00	$225,840.00
43	931 Main	Roman Catholic Bishop of Worcester	4	5	3	0	High	12	$85,670.00	$121,990.00
44	46 Wellington	Wellington Company	5	0	4	3	Neutral	12	$259,550.00	$356,350.00
45	872 Main	Zi Feng Li	3	5	3	0	Neutral	11	$81,116.00	$115,852.00
46	880 Main	Cultural Ctr Hrisohorafiton	3	5	3	0	Neutral	11	$96,020.00	$135,940.00
47	6 Ripley	Main South CDC	5	2	4	0	High	11	$99,999.00	$141,303.00
48	25 Ethan Allen	Wellington Company	5	0	5	0	Neutral	10	$85,900.00	$122,300.00
49	9 Hammond	All Realtime Realty LLC	2	5	3	0	Neutral	10	$27,871.00	$44,087.00
50	64 Jackson	US Sprint Communications Company	4	1	4	1	Neutral	10	$137,351.00	$191,647.00
51	934 Main	Clark University Trustees	2	5	3	0	Neutral	10	$101,770.00	$143,690.00
52	45 Wellington	Chestnut Renweal Cooperation	5	0	4	0	Neutral	9	$59,105.00	$86,185.00
53	49 Wellington	Chestnut Renweal Cooperation	5	0	4	0	Neutral	9	$96,250.00	$136,250.00
54	36 Gates	Main South CDC	2	1	5	0	High	8	$65,660.00	$95,020.00
55	23 Wellington	Wellington Company	5	0	3	0	Neutral	8	$116,720.00	$163,840.00
56	37 Wellington	Chestnut Renweal Cooperation	5	0	3	0	Neutral	8	$58,300.00	$85,100.00
57	1 Kilby	Garry G. Dutram	2	1	4	0	Neutral	7	$79,000.00	$113,000.00
58	767 Main	Standish Apartments Ltd Partner	5	5	2	0	High	12	$118,100.00	$165,700.00

Summary

The goal of our project was to determine the feasibility of installing green roofs in two locations and determine other possible sites in the Main South community. To accomplish this we:

- Determined the weight ranges of typical green roofs
- Found the structural capacities of the roofs based on their current designs
- Determined more specific criteria about what makes a building suitable for a green roof
- Determined the average cost associated with green roofs in this area
- Identified other potential sites for green roofs.

The combination of these steps created the foundation required to enable the building of green roofs within Main South.

Our results from determining the weight of a typical green roof showed that there can be a range in weight from **11 psf to 80+ psf**. We moved forward with a structural analysis of the MSCDC's maintenance garage on Kilby Street and the WCUW Radio building on Main Street.

The findings from the structural analysis showed that **both buildings were insufficient to support a green roof**. In order to address this we moved forward with conducting a cost analysis.

We determined that due to the large number of buildings with potential to hold a green roof it would **be advantageous to identify other sites** located in Main South. We moved forward by investigating other potential sites and raking them in comparison to each other.

Our results showed that the **sites listed in Table 11 are the best options for further research** and possible implementation of green roofs. We recommend that **the sites in Table 11 be contacted and informed of their potential** to serve as demonstration sites for green roofs in the Main South Community. We recommend that a structural analysis be performed on each of these sites in hopes that at least one will not need any structural modification in order to support a green roof.

It is our hope that with further investigation of these sites that green roofs could become a real possibility in the Main South Community. If this all takes root, our project will have served as a catalyst towards getting green roofs installed throughout the community and an important first step towards improving the quality of life for the residents of Main South.

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Appendix A: Interviews

A.1: Chase Terrio

WPI-IQP: MSCDC Green Roofs
Interview with Chase Terrio Minutes

10/28/10

10:17am-10:48am

Type of Meeting: Phone Interview

Meeting Facilitator: Ricky Holak

Invitees: Ricky Holak, Chase Terrio, Ryan Wallace, Matt Paladino, Alford Green

I. Description of project goals and current status of our work.

II. Questions

1. What experience do you have in working with green roofs?
    - i. Was a superintendent on the J.W. McCormack Federal Courthouse and Post Office which was completed in 2009. It was a federal building in downtown Boston which was 23 stories high and was completely renovation to become LEED gold certified.
    - ii. Green roofs were installed on the 4th and 5th floors with both an intensive section and a modular section.
  - b. Do you have specific cost data you can share?
    - i. No, was a superintendent so was more focused on installation.
  - c. Do you have any loading data you can share?
    - i. Contact Western Solutions
  - d. Do you have and scheduling of installation you can share?
    - i. Intensive- built "giant bathtub" 40'x 85'x 3' and used crane to load "tub" and soil onto the rooftop.
    - ii. Modular- Much less labor intensive. Required more coordination in terms of modules being brought in orderly fashion. Much less protection required for roof because modules act as a barrier between roof and soil.
    - iii. Modular Assembly-
        1. Started with generic cold applied four-ply roof, which is durable and thick.
        2. Installed roof barrier which was basically a thick plastic layer to protect roof from modules.
        3. Installed a drainage mat which was basically a "waffle pad" to lift everything off roof about a half inch so that water can drain.

4. Installed modules on top of drainage mat.
5. Lined modules with filter fabric to prevent washout of soils during rainfall. Fabric was spread over all modules so that they were hidden and it looks like one large pot.

e. How difficult is it to install a green roof?
    i. Module labor for McCormack building included 1500 modules and took 8 guys 10 days to install. This included an irrigation system between modules which was a very time consuming factor.
    ii. Not sure if irrigation system was needed. Many variables are considered including type of plants and water dependency.
    iii. Don't necessarily need to hide modules. McCormack project was above and beyond.
    iv. Intensive roof for McCormack building was 3' deep and took far more preparation. Additional concerns for loading were considered for additional structural support.

f. What is the maintenance like on a green roof?
    i. McCormack building maintenance package includes a visit once a month from May 1st to November 1st for weeding, dead leaves, debris. Also irrigation system must be drained for winter.
    ii. This maintenance plan is not required for all green roofs.
    iii. Minimal maintenance on modules.

g. Have you ever come across uninstalling a green roof and what would it cost? If not, can you guess about the procedure and costs?
    i. Would be very labor intensive.
    ii. Installing the McCormack green roof a crane with 6 men loaded 150 cubic yards of soil onto roof in 2 hours. They noticed that the drainage mat was upside down and needed to be flipped over. 12 men were hired to hand shovel the soil off which was a 3 week process and very costly.

2. From your experience what differences do you see modular green roofs and traditional green roofs?
    i. Modular green roofs were much cheaper and quicker to install. Would recommend modular green roofs.
3. In general, when you add weight to a roof, what procedures do you typically follow?
    i. McCormack was reinforced concrete so structure was not an issue.
    ii. Typically a structural engineer would go to the building, measure supports and provide a drawing of the building. They would label supports and run calculations to provide roof strength limits.
    iii. Suggest contacting structural engineer.

        iv. Generalize conditions and provide some worst case scenario calculations.
   b. We have ASTM standards, and are trying to contact the city of Worcester
   c. Do you have any contacts from the city who could help us?
   d. Should we get the weights of actual materials used from subcontractors?
        i. Western Solutions was manufacturer of modules. Can get in contact with Jared Markham who was project manager. Western organized installation, facilitated propagation of plants and soil mixture from green house. Would have statistics on soil properties.
4. Would you be able to give us contact information of roofing subcontractors you've used in the past?
   a. Western Solutions, Jared
5. From our reading we have found that locating leaks in the waterproofing is a typical concern with involved with green roofs. Have you had any experience with this?
        i. If leaks occur in modular section you can simply pull out modules individually to repair leak which is another advantage over intensive.
        ii. McCormack building did no use electronic grid on intensive green roof to locate leaks.
        iii. Roofing warranty should cover leak regardless.
6. Do you know of any additional resources that might be helpful?
   a. Valley Crest Landscaping, worked with Western Solutions for installation of both roofs. Would have labor incite and could provide rough cost estimates.

A.2 Neil Benner

WPI-IQP: MSCDC Green Roofs
Interview with Neil Benner Minutes

10/29/10
10:00am-10:35am

Type of Meeting: Personal Interview

Meeting Facilitator: Alford Green

Invitees: Alford Green, Neil Benner, Ricky Holak, Ryan Wallace, Matt Paladino

I. Description of project goals and current status of our work.
II. Questions
    1. What experience do you have in working with green roofs?
        i. Was project manager for East Hall.
        ii. East Hall- Extensive green roof with 2'x2' modules. Trays are visible now, eventually will be covered by plants.
    b. Do you have specific cost data you can share?
        i. Cost will include:
            1. Structural Analysis and Design for modifications
            2. Actual structural construction
            3. Roofing evaluation
            4. Green roof design and manufacturing price.
            5. Installation of roofing and green roof.
        ii. Compile several estimates for each to get best prices.
        iii. Two biggest cost variables include structural changes and roofing material.
        iv. Try to find an engineer part of a non-profit who could look at building for structural design.
        v. After evaluation: bundle green roof installation, roofing, and permits into one bid.
        vi. By doing homework beforehand and getting to source you will have better idea and get a more competitive bid.
    c. Do you have any loading data you can share?
        i. Have loading data for extensive example of 2'x4' modules.
    d. Do you have and scheduling of installation you can share?

i. For East Hall the plants were planted in the nursery in April, 2008.
ii. August 2008 roof was installed.
iii. Total of about 9 months to a year for East, retro fit could be more like 6 months.

e. How difficult is it to install a green roof?
   i. Most likely wouldn't need general contractor. Would need someone who is familiar with construction.
   ii. First thing to look at is how much natural light the roof gets.
   iii. Look at roof material and warranty information.
   iv. Find vendor who specializes in green roof. They will look at specific climate and recommend certain type of plants. Variables- wind, natural light, rain, etc.
   v. Jared Markham did this for East.
   vi. Architect specified project. Jared decided on modular green roof and type of plants.
f. Have you ever come across uninstalling a green roof and what would it cost? If not, can you guess about the procedure and costs?
   i. Modules would be much easier to uninstall.

2. From your experience what differences do you see modular green roofs and traditional green roofs?
   a. Do the aesthetics turn people away?
      i. Intensive plants are planted on rooftop. May be more natural looking.
      ii. Leaks can be a nightmare for intensive.
3. In general, when you add weight to a roof, what procedures do you typically follow?
      i. Look at condition of roofing membrane. Evaluate steel.
      ii. Will need to hire structural engineer to review existing roof structure and decide if roof can handle load. Cannon Design could help with some cost estimates.
   b. We have ASTM standards, and are trying to contact the city of Worcester
      i. Go to city office, phone calls can be ineffective.
   c. Do you have any contacts from the city who could help us?
      i. Contact Mary Salmon for permit information. 25 Meade St.
4. Would you be able to give us contact information of roofing subcontractors you've used in the past?
   a. Titan roofing- Located downtown they do a lot of work in the area. Could contact them for an estimate.
5. We noticed that East Hall had a white rooftop on the areas that were not vegetated. Is this common?

a. White roofs reflect heat to lower air conditioning costs. Black roofs absorb heat and increase air conditioning costs. Most LEED buildings with flat roofs are white including the new Recreation Center at WPI.

A.3 Lynne Deninger

WPI-IQP: MSCDC Green Roofs
Interview with Lynne Deninger Agenda

10/29/10
1:30pm

Type of Meeting: Phone Interview

Meeting Facilitator: Alford Green

Attendees: Alford Green, Lynne Deninger, Peggy Middaugh, Ricky Holak, Ryan Wallace, Matt Paladino

III. Description of project goals and current status of our work.
IV. Questions
   1. Can you tell us what you know about the costs of green roofs?
      a. Cost is always a factor. You do not just need to worry about the roof cost, but the cost of structural modifications or additions, and additional support or piping. Modular trays usually cost between \$50-\$40 per square foot, but intensive is \$50 and up. Each one is specially designed, so it is hard to say. Also, what do you include? Do you include structural modifications if they are needed? It is hard to give a specific price because designs vary so much.
   2. Do you have any information regarding energy savings associated with green roofs?
      a. No. You can go online and find the heating and cooling savings for green roofs with about 4 inches of soil. Intensive green roofs will have a higher level of energy savings because they have a continuous plane of soil, while modular roofs, because of the egg crate quality of the trays, trap air amongst the roof surface and the trays.
   3. Can you tell us about the green roof at East Hall at WPI?
      a. East Hall was not designed for a full green roof. It had been talked about in the initial design, but it was decided not to design one. They were not sure if they

could have pulled it off financially. The roof at East Hall cost around $30-$40 per square foot. The green roof at East Hall was built more for visual appeal and to study the effects it has on runoff rather than for energy savings. The green roof and white roof were put on East Hall for the visual appeal of people looking down on it from up on the hill. They are using the green roof and white roof to compare the runoff from a conventional and green roof on East Hall.

4. Can you tell us how difficult is it to install a green roof?
    a. You need to look for a good roofing contractor to use. Find one who has experience installing green roofs. There were no difficulties with the East Hall roof, it went very smoothly.
5. What considerations, other than weight, do you use when selecting vegetation?
    a. You need to look at where the roof is going, and how it's going to be structurally supported. For example, at East Hall, it had been discussed in design, but not included in the full building design at the very beginning. Therefore, finding the building's ability to hold anything heavier than what was finally selected was very difficult. You also need to look at who has access to the roof, and for what reason. At WPI, the roof acts an as amenity to those looking down on it from the hill, it is also used for researching the water quality, quantity, and temperature of the water running off from each roof. It was not difficult to install those tiles, and it did not have to be perfect, because nobody was accessing it and looking closely at the roof. Where people access the roof regularly, you need to approach it differently, and take the appearance into more consideration. Another important thing to consider is what maintenance is involved with the roof. You need to know how much ongoing maintenance will be involved with the roof, and how you will deal with it. You also need to take into account the maintenance of the plants themselves. As for the roof structure, nothing was needed below the system we installed at East Hall, but if you have to modify the roof, you will need to have a very intricate roof detail, the more intricate the detail, the more intense it will be. At WPI, the plants are short-rooted, and stay within the trays, so a root barrier was not absolutely necessary. As roofs get more intensive, they may need to be irrigated, the plants at WPI are very drought-tolerant and water themselves with the water they sequester from rainfall. A couple of examples of more intensive roofs are at the Simmons School of management, where they wanted an outdoor terrace that could be used for entertaining and having events. There is a large patio and many small to mid-sized shrubs there. Also, at Post Office Square, they wanted to have trees put in so the roof could be used as a year-round park. A lot of it depends on the intended purpose of the roof.

6. Would you be able to give us contact information of roofing subcontractors you've used in the past?
    a. At WPI, we used Weston Solutions to install the roofs. What typically happens is that roofing contractors will do the roofing work and then bring in a landscaper to install the actual plantings. You can search "green roof installers" on Google and you'll probably get a lot of results.

A.4 Melissa Bezanson

WPI-IQP: MSCDC Green Roofs
Interview with Melissa Bezanson Agenda

11/3/10
10:15am

Type of Meeting: Phone Interview

Meeting Facilitator: Ricky Holak

Invitees: Ricky Holak, Melissa Bezanson, Alford Green, Ryan Wallace, Matt Paladino

V. Description of project goals and current status of our work.
VI. Questions
1. Loading
    a. Do the weights listed in your specifications include the water proofing systems and membranes?
        i. No they do not
    b. Do you have a recommended water proofing membrane? What is its weight per sq./ft.?
        i. No, I would suggest you go to a manufacturer. You can talk to Steve Benjamin, a technical manager from Carlisle Waterproofing. His number is 413-262-8928, and I'll send you his contact information in email. Our systems can be installed on just about any roofing membrane, like rubber or EPBM. The only exception is that we cannot install our system on asphalt shingles.
    c. Do you have a recommended drainage mat? What is its weight per sq./ft.?
        i. No, usually the drainage mat used is determined by roofer, we do not require any drainage mat through our specifications. Our modules have a

waffle texture on the bottom that acts a drainage mat. As far as weights, the geotextile slip sheet weights about 6 ounces per square foot, it is basically weed fabric doubled over. It protects the roof between the module and membrane, in case some of the growing media falls out of the modules and the installer isn't very careful about sweeping, you could run the risk of rock penetrating your roofing membrane without the geotextile layer.

2. Growth media
    a. Do you have a more detailed fact sheet about your growth media?
        i. I have forwarded you results from a Penn State study handout. It gives information about wet and dry densities of growth media. Our growth media is regional, so it varies based on where in the country you are. We use local materials because it is easier to acquire them. In the northeast, we use a biosolid compost that is locally derived. Our aggregates are expanded shale and mixes fines from upstate New York. They range in size from 3/8 in. to sand. This is 15% of the growth media. The biosolid compost is 10%.
        ii. Do you have weights of oven dry vs. saturated?
            1. These are in the Penn State document
        iii. Do any of your growth media produce less phosphate runoff?
            1. This information can also be found in the document I sent to you
    b. Can you tell us more about your Ecoballast growth media?
        i. I've never actually used it. Basically it is river rock that we put into our trays, there is no plant material, it is just for storm water retention. You do retain some water with this system, but no to the same magnitude of our plant roofs. I have never seen a whole roof done with it, usually it is for around roof drains or the perimeter. It is also used as an aesthetic accessory.
    c. Do you have a measure R-value for any of your growth media?
        i. Not that I'm aware of. It is extremely difficult to measure an R-value for green roofs. As evapotranspiration occurs, the soil gets more or less moist, and it is hard to get a defined R-value for green roof media. You get an R-value from the membrane, and the material over it disguises the value. Also, there is a fluctuation of temperatures in the soil. I have no idea how to even try to obtain an R-value from green roof media.
    d. What can we gain by using deeper soil depths?
        i. There will be an increase in storm water runoff, but not much of an additional energy savings, it would be pretty minimal. Another benefit of

the 8" trays over the 4" trays is that you do not have to worry about wind uplift. If you are in a high wind area this may be a concern. We had a client in a hurricane region, and they were afraid to go with the 4" trays, which only weigh 120 lbs. for a 2x4 tray, whereas the 8" trays weigh in at 320 lbs. for the same size tray. With wind it all depends. You have to see what your insurance wants, and it also depends on if you have a parapet or not. You can look at SPRI regulations for this information. There is no way to measure wind uplift potential, it would be very costly to conduct an extensive wind study for every project, you just have to rely on the insurance companies, which are usually overcautious. We've only ever had one project get cancelled because of wind. At FM Global in Connecticut, we installed the roof, but the inspector failed us because he was worried about the growth media becoming a projectile and shattering a window. The way to minimize this is that we try to have 80-100% growth coverage in the trays before placement. You can also use a juke mat, it is a soil stabilizer, that they usually use to put sod on inclines.

3. Vegetation
    a. Do you have a listing of you preset "pallet" of plants?
        i. How were these pallets selected?
            1. Our selection is regionally driven. In New York City, we can use less rugged material than somewhere farther up in New England. In Connecticut and Massachusetts, we pick pants that tolerate zone 6, and are drought resistant, but we are very flexible based on what the client desires. We work with the nursery, building owner, and design team to produce an aesthetically pleasing rooftop. In the 4 in. modules, we usually select sedums, chives, prickly pear cactus, and maybe some certain grasses. In the 8 in. trays, it is a whole different story. There is a lot more flexibility in these trays. We usually choose the sedums by color, growth habitat, and evergreen capability, but again it all goes back to what the client is looking for. The preferred plant pallet for the 4" trays is using rugged sedum varieties, we typically prefer to use 5 species. Plants usually grow three times slower up on the roof because of the intense sunlight, heat, drought, and wind. Last summer was tough for us, it really helped us to refine our plant list in include only the most rugged varieties.
    b. What if we told you that our site has an EPA grant for storm water retention and public education?

1. If you are looking to sequester more storm water, use the 8" trays. They hold much more. The 4" trays sequester about 40% of runoff, though.

c. What if we wanted to grow food?
   i. Well you would have to modify the soil mix. The biosolid we use is not for food growing, you would have to use leaf compost. Also, more organics would be needed. This would result in an increased weight for the growth media. Also, you would need mulch, and to replant the crops each season. You are also talking about a huge increase in maintenance; there is the added cost of irrigation as well. Another thing to consider is that as you use more organic compounds, it makes for increased weed growth. I would say you absolutely need to use at lest the 8" modules for growing food. If you wanted to use different types of modules, we are flexible with that as well.

d. Any other considerations we should make with plant selection?
   i. The plant material we usually use flowers in May or June through August. There would be no mowing or deadheading required for the plants we typically use. Also, the sedums are self-propagating. They do not need seeds to germinate new plants. They use their own foliage to sprout new roots. So if you were up on the roof walking over the trays and stepped on a stem and broke it, as long as it gets pushed down into the soil it will usually germinate a new plant. We use either plugs or cuttings for our plantings. The plugs are about the diameter of a 50 cent coin. If you are using cuttings, you need to wet the soil first, then put down seed mulch, apply the cuttings, they go at about 1 lb. per 4 square feet. Then you need to apply root hormone gel on top, and intensely water the plants for six weeks. This will help you get coverage much faster. We can also use native plantings. These will require a heavier soil. I do not have any data on our soil blend for native plants; it was just brought on this year. I know UVM is looking to do a project using native plantings. Also, the McCormack building you spoke to Chase about is all native plantings. That is what the EPA wanted. It works well on their roof. They get about only 2 hours of sun daily, it is very shady, and constantly wet, so it is well-suited for native plantings. There is a debate going on in the industry involving native plantings. Many people are arguing that by putting plants on the roof of a skyscraper, you are redefining what is native to that environment, because it is very different than at ground level on the same site.

4. Costs
    a. Membranes ($/area)
        i. This is also in the document I sent. You can talk to Steve Benjamin about this as well.
    b. Modules
        i. The pricing driven by project size. I'll give you some price points. For a roof that is less than 1000 square feet, it costs about $20 per square foot. For a roof that is about 5000 square feet, it costs about $14 per square foot. This includes everything. The trays are pre-planted and come palletized or on racks and are delivered curbside. You just need a roofer to install them, or a landscaper. If you are going to have community members help you, you have to worry about fall protection and OHSA requirements. For roofs over 10,000 square feet, it will cost about $11-12 per square foot. You can bid both roofs together, order them together, and have them delivered separately, to lower your unit costs. These prices are all for the 4" trays. I do not have any exact numbers for the 8", but they usually come at a 7-8 dollar premium over the 4" trays. Also, the 2.5" trays are the same price as the 4". We don't like to use these, they require a lot of extra care, the trays run out of water, it greatly restricts the wind pallet & the plant pallet, and you need to irrigate them.
    c. Maintenance
        i. Many companies will tell you that their systems require no maintenance. This is not true. Any system is going to need maintenance, especially if we have another summer like last one. Without proper maintenance, the roof will die. You need to weed the trays. Weeds will deplete the soil nutrients and choke out the species we want growing there. Also watering is another important thing to consider. Sedums can go for two weeks without water, and at this point they will not die, but start to look very stressed. Eventually it will stunt their growth for subsequent years. You need to water them at the two week point without at least an inch of rainfall. We also recommend two major weeding events each year. During the first week of June and mid-September usually work the best for this. The warranty on the Carlisle products includes the waterproofing, and removing modules to fix it. If the system leaks or the roof needs to be fixed, you can just move the trays, stage them somewhere else, and move them back when you are finished.
5. Other Questions:

a. What do you know about Apex's mat system?
    i. It is very different from ours. They try to compare the two side-by-side, but they are two very different systems. Once their soil mat is removed, their system is just like a traditional built in place green roof. You also need to use edging around the exterior (if there is no parapet), and around every vent of chimney that extrudes through the roof surface.
b. What about the aluminum edging you sell?
    i. That is purely aesthetic. It is just there for looks.
c. Also, what if the building owners decided for some reason to have their roof removed?
    i. It is as easy as taking the trays down, and you are left with a roof that has additional membranes.

A.5: Casey Burns

WPI-IQP: MSCDC Green Roofs
Interview with Casey Burns Agenda

11/3/10
1:00pm

Type of Meeting: Personal Interview

Meeting Facilitator: Alford Green

Attendees: Alford Green, Casey Burns, Ricky Holak, Ryan Wallace, Matt Paladino

VII. Description of project goals and current status of our work.
VIII. Questions
1. Do you have any experience working with green roofs?
-No.

    a. Has Youth Grow done any projects involving green roofs?
    -No, because "there have been easier ways to do gardening."
2. Would Youth Grow be interested in being a part of this project by growing crops on these green roofs?
-Yes. "We look a lot to partners...with an organization like the CDC we would be really excited."
3. What types of crops does Youth Grow cultivate?

-Lettuce, greens, tomatoes, egg plants, peppers, hot peppers, corn. "…culturally specific crops- Asian greens, specialty hot peppers; depending on the community that's gardening around." "We have moved a little bit more with our youth program of growing fruit… some berry bushes…"

a. Are there any special requirements (soil depth, nutrients, etc.) for these crops?
   -"We use the city's composting program for all our soil… and we have a lot of success with it." Soil composition is not a major problem unless specialty crops were being grown.
   -"It depends on what you were growing. We grow in raised beds now…we've done it with 3-ft. depth." "Lettuces or micro-greens it's gonna be much lower."
b. What is the growing season for these crops?
   -"…start planting late March and we pull-out our crops in November."
c. Will they need to be replanted after harvesting?
   -"A lot of those basic vegetables that I mentioned are what you have to plant every season and that is the majority of stuff that we do." Strawberries, asparagus and berry bushes don't have to be replanted.
d. How much maintenance do these crops need?
   -"During peak season they need daily maintenance. We do all of our farming pretty low-tech so that increases the labor intensity of it, but we also have a lot of teenagers who work on the farm… We don't have irrigation systems… but with an irrigation system that's less of a burden where maybe you can do it more like a few times a week, but I think at least that to do weeding and mulching."

Appendix B: Truss Calculations

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Influence Lines - Calculations:

A_y: $\circlearrowright \Sigma M_o = 0 = (-1)(596.25 - x) + A_y(596.25)$

$596.25 A_y = 596.25 + x$

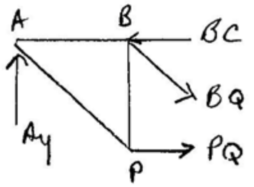
$A_y = 1 - x/596.25$

x	A_y
0	1
52	0.912788
96.75	0.816152
141.5	0.762683
186.25	0.687631
231	0.612579
275.75	0.537526
298.125	0.5
320.5	0.462474
365.25	0.387421
410	0.312369
454.75	0.237317
499.5	0.162264
544.25	0.087212
596.25	0

O_y: $\Sigma F_y = 0 = -1 + A_y + O_y$

$O_y = 1 - A_y$

x	A_y	O_y
0	1	0
52	0.912788	0.087212
96.75	0.816152	0.162264
141.5	0.762683	0.237317
186.25	0.687631	0.312369
231	0.612579	0.387421
275.75	0.537526	0.462474
298.125	0.5	0.5
320.5	0.462474	0.537526
365.25	0.387421	0.612579
410	0.312369	0.687631
454.75	0.237317	0.762683
499.5	0.162264	0.816152
544.25	0.087212	0.912788
596.25	0	1



$$\Sigma F_y = 0 = A_y - BQ \sin 31.8$$
$$BQ = \frac{A_y}{\sin 31.8}$$

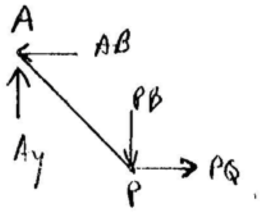
x	BQ
0	0
52	-0.165502 (c)
96.75	1.54891 (T)
141.5	1.44734
186.25	1.30491
231	1.16248
275.75	1.02006
298.125	0.948846
596.25	0

$$\circlearrowleft + \; \Sigma M_p = 0 = BQ \cos 31.8 \,(27.75) + A_y (52) - BC\,(27.75)$$
$$BC = \frac{BQ \cos 31.8\,(27.75) + A_y (52)}{27.75}$$

x	BC
0	0
52	1.56979 (c)
96.75	2.84569 (c)
141.5	2.65926
186.25	2.39757
231	2.13588
275.75	1.8742
298.125	1.75026
596.25	0

$$\Sigma F_x = 0 = BQ \cos 31.8 - BC + PQ$$
$$PQ = BC - BQ \cos 31.8$$

x	PQ
0	0
52	1.71045 (T)
96.75	1.52937 (T)
141.5	1.42918
186.25	1.28854
231	1.1479
275.75	1.00726
298.125	0.943843
596.25	0

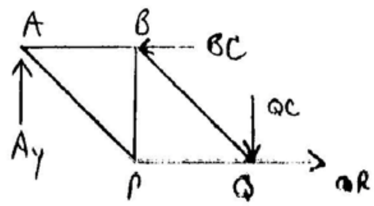


$\Sigma F_y = 0 = A_y - PB$
$PB = A_y$

x	PB
0	0
52	0.912788 (c)
596.25	0

$\Sigma F_x = 0 = PQ - AB$
$AB = PQ$

x	AB
0	0
52	1.71045 (c)
596.25	0

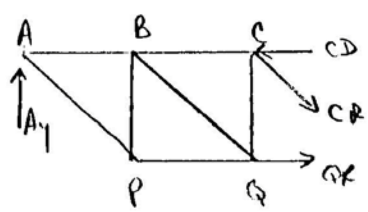


$\Sigma F_y = 0 = A_y - QC$
$QC = A_y$

x	QC
0	0
96.75	0.816152 (c)
596.25	0

$\Sigma F_x = 0 = QR - BC$
$QR = BC$

x	QR
0	0
96.75	[illegible]
141.5	[illegible]
186.25	2.39957
231	2.13577
275.75	1.8142
298.125	1.75026
596.25	0

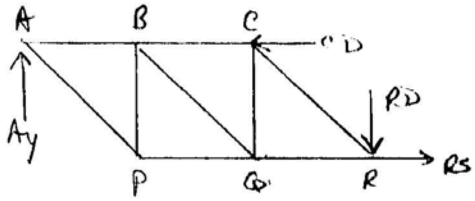


$\Sigma F_y = 0 = A_y - CR\sin 31.8$
$CR = \frac{A_y}{\sin 31.8}$

x	CR
0	0
96.75	-0.348887 (c)
141.5	1.44734 (T)
186.25	1.30491
231	1.16248
275.75	1.02006
298.125	0.948846
596.25	0

$\Sigma F_x = 0 = QR + CR\cos 31.8 - CD$
$CD = QR + CR\cos 31.8$

x	CD
0	0
96.75	2.54917 (c)
141.5	3.88934 (c)
186.25	3.50666
231	3.12386
275.75	2.74114
298.125	2.55668
596.25	0

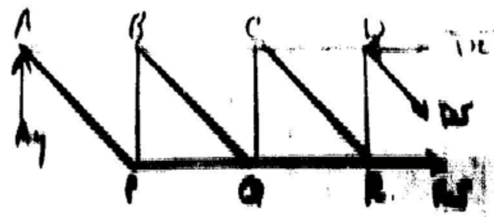


$\Sigma F_y = 0 = A_y - RD$
$RD = A_y$

X	RD
0	0
141.5	0.762683 (C)
596.25	0

$\Sigma F_x = 0 = RS - CD$
$RS = CD$

X	RS
0	0
141.5	3.88934 (T)
186.25	3.5066 (T)
231	3.12386
275.75	2.74114
298.125	2.55668
596.25	0

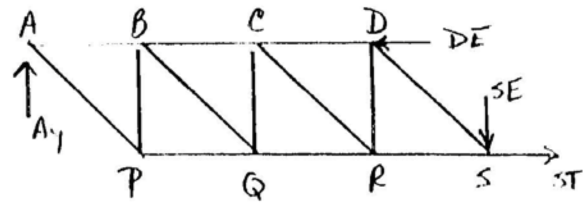


$\Sigma F_y = 0 = A_y - DS\sin 31.8$
$DS = \frac{A_y}{\sin 31.8}$

X	DS
0	0
141.5	-0.145055 (C)
[illegible]	[illegible]
[illegible]	[illegible]
[illegible]	[illegible]
298.125	[illegible]
596.25	0

$\Sigma F_x = 0 = RS + DS\cos 31.8 - DE$
$DE = RS + DS\cos 31.8$

X	DE
0	0
141.5	3.50659 (C)
186.25	4.61563 (C)
231	4.11184
275.75	3.60808
298.125	3.3631
596.25	0

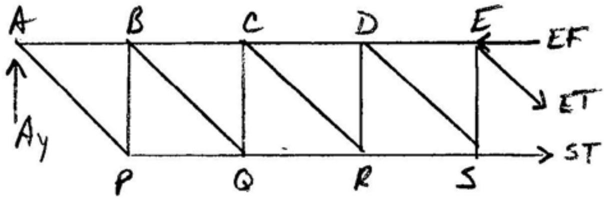


$\Sigma F_y = 0 = A_y - SE$
$SE = A_y$

X	SE
0	0
186.25	0.687361 (C)
596.25	0

$\Sigma F_x = 0 = ST - DE$
$ST = DE$

X	ST
0	0
186.25	4.615163 (T)
231	4.11184 (T)
275.75	3.60808
298.125	3.3631
596.25	0



$\Sigma F_y = 0 = A_y - ET \sin 31.8$

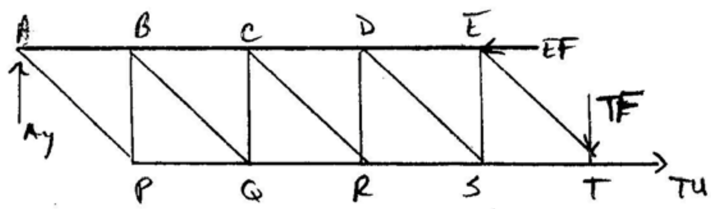
$ET = \dfrac{A_y}{\sin 31.8}$

X	ET
0	0
186.25	-0.592211 (c)
231	1.16249 (T)
275.75	1.02006
298.125	0.948846
596.25	0

$\Sigma F_x = 0 = ST + ET\cos 31.8 - EF$

$EF = ST + ET\cos 31.8$

X	EF
0	0
186.25	4.11231 (c)
231	5.09983 (c)
275.75	4.47502
298.125	4.16952
596.25	0



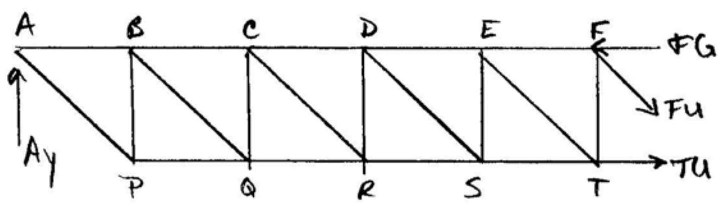
$\Sigma F_y = 0 = A_y - TF$

X	TF
0	0
231	0.612579 (c)
596.25	0

$\Sigma F_x = 0 = TU - EF$

$TU = EF$

X	TU
0	0
231	5.09983 (T)
275.75	4.47502 (T)
298.125	4.16952
596.25	0



$\Sigma F_y = 0 = A_y - FU \sin 31.8$

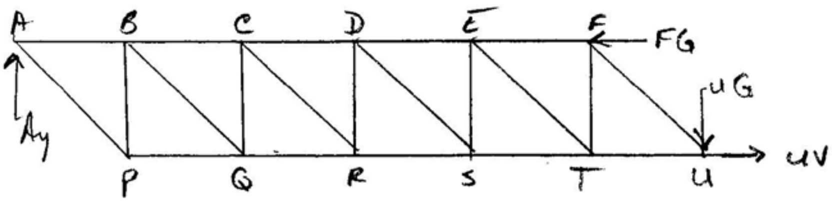
$FU = \dfrac{A_y}{\sin 31.8}$

X	FU
0	0
231	-0.735206 (C)
275.75	1.02006 (T)
298.125	0.948846
596.25	0

$\Sigma F_x = 0 = TU + FU\cos 31.8 - FG$

$FG = TU + FU\cos 31.8$

X	FG
0	0
231	4.47498 (C)
275.75	5.34196 (C)
298.125	4.97594
596.25	0

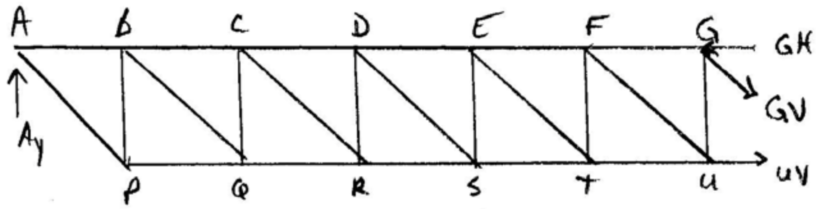


$\Sigma F_y = 0 = A_y - UG$
$UG = A_y$

x	UG
0	0
275.75	0.537526 (C)
596.25	0

$\Sigma F_x = 0 = UV - FG$
$UV = FG$

x	UV
0	0
275.75	5.34196 (T)
298.125	4.97597 (T)
596.25	0

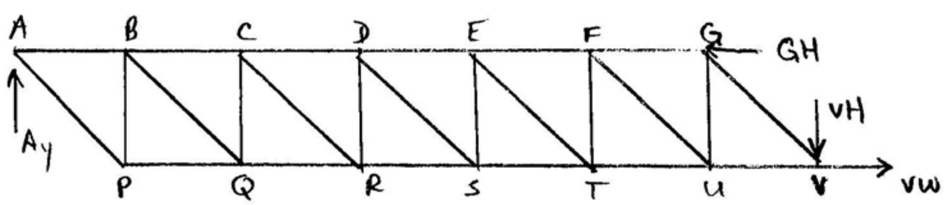


$\Sigma F_y = 0 = A_y - GV \sin 57.12$
$GV = \dfrac{A_y}{\sin 57.12}$

x	GV
0	0
275.75	-0.594087 (C)
298.125	0.642292 (T)
596.25	0

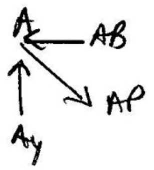
$\Sigma F_x = 0 = UV + GV \cos 57.12 - GH$
$GH = UV + GV \cos 57.12$

x	GH
0	0
275.75	4.96906 (C)
298.125	5.37913 (C)
596.25	0



$\Sigma F_y = 0 = A_y - VH$
$VH = A_y$

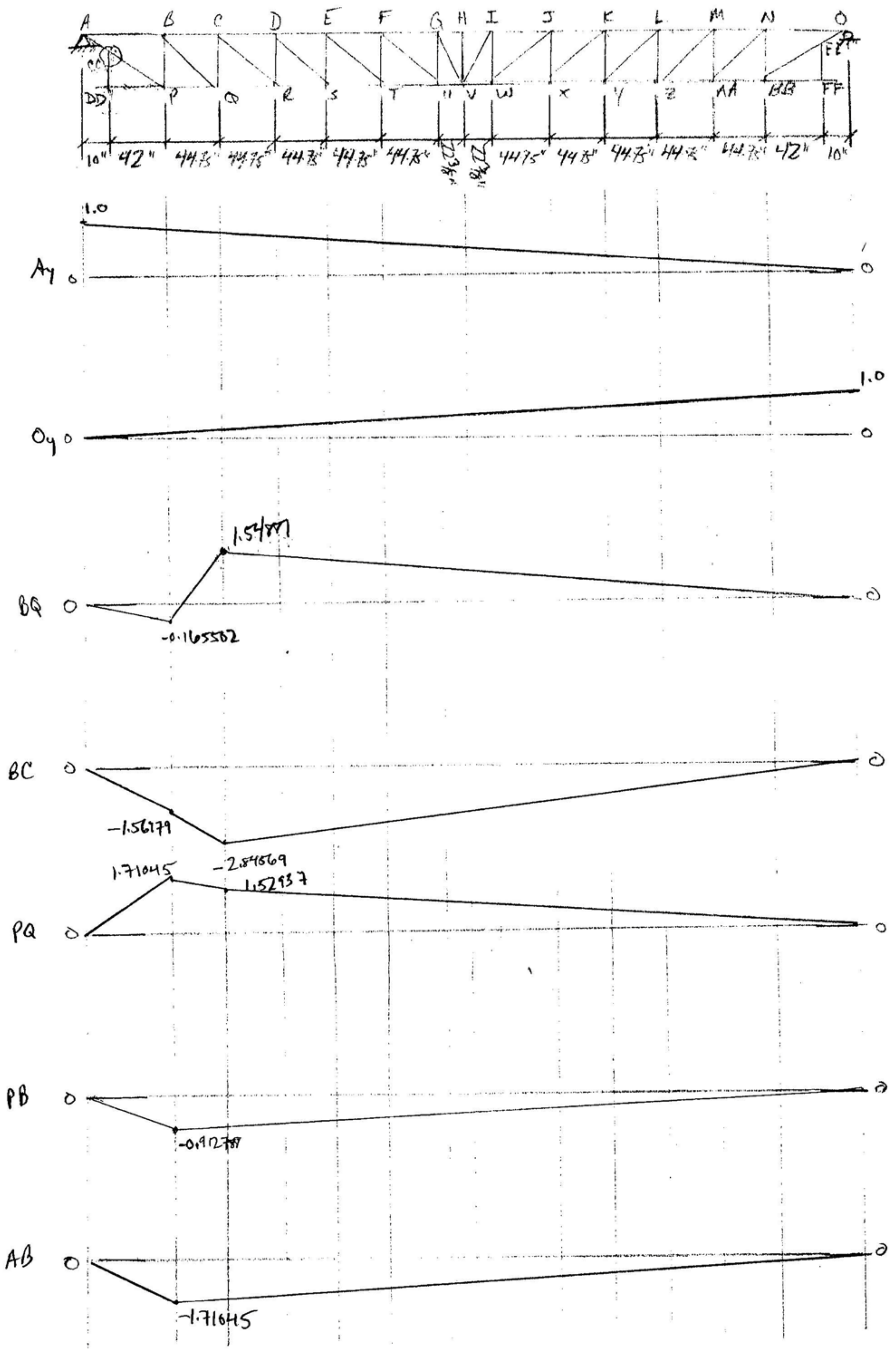
x	VH
0	0
298.125	0.5 (C)
596.25	0



$$\Sigma F_y = 0 = A_y - AP \sin 29.09$$

$$AP = \frac{A_y}{\sin 29.09}$$

x	AP
0	0
52	1.87746(T)
596.25	0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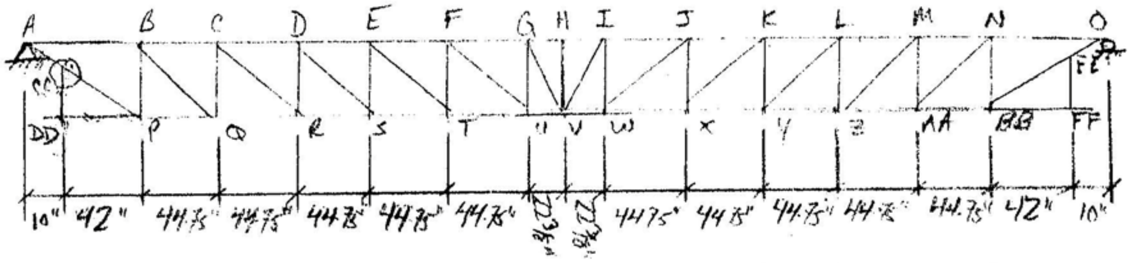
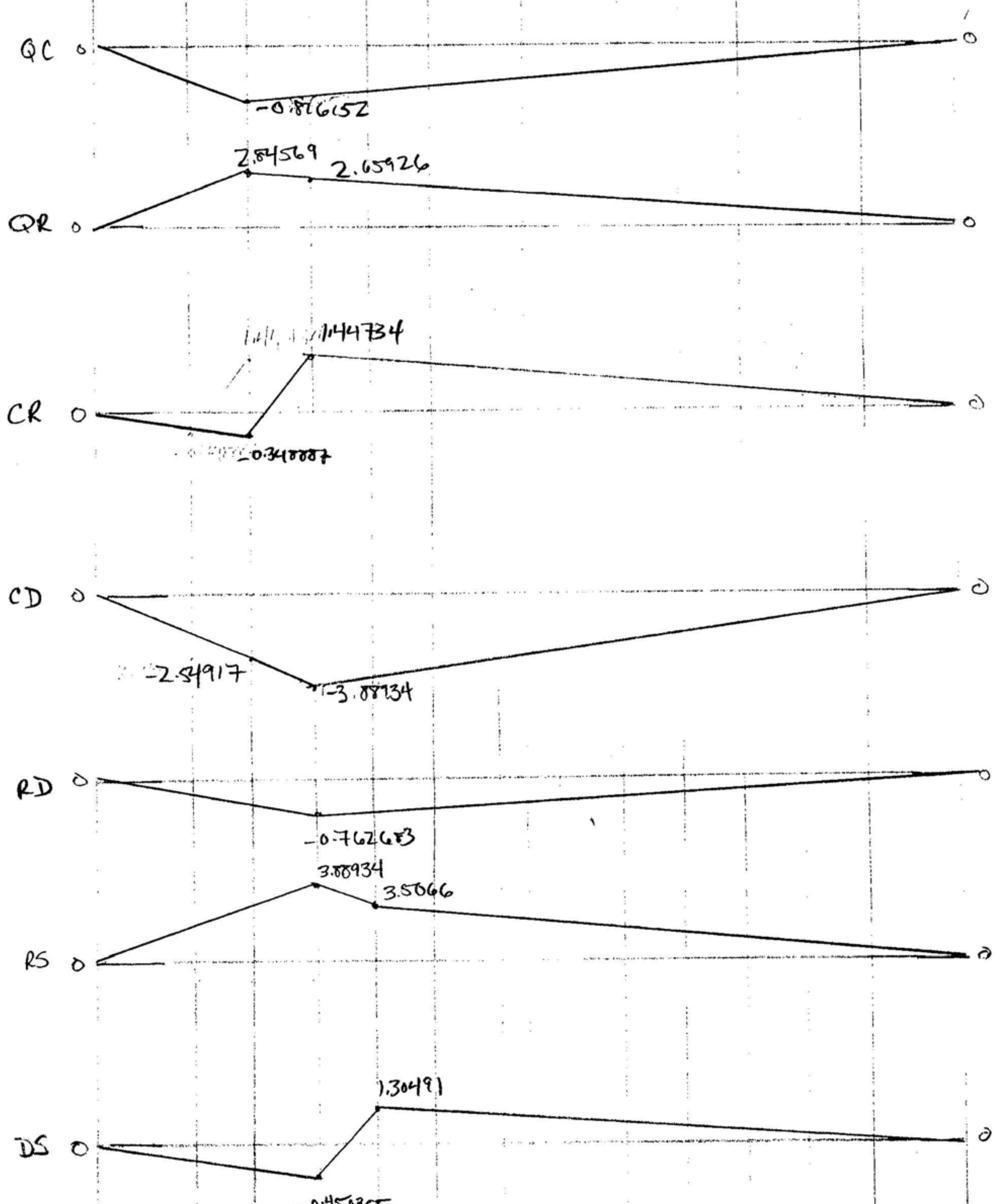
CC DD P Q R S T U V W X Y Z AA BB FF EE
10" 42" 44.75" 44.75" 44.75" 44.75" 44.75" 22 3/8" 22 3/8" 44.75" 44.75" 44.75" 44.75" 44.75" 42" 10"
Ay 1.0 0 0
Oy 0 1.0 0
BQ 0 1.54877 -0.165502 0
BC 0 -1.56179 -2.84569 0
PQ 0 1.71045 1.52937 0
PB 0 -0.192787 0
AB 0 -1.71045 0


A B C D E F G H I J K L M N O
CC EE
DD P Q R S T U V W X Y Z AA BB FF
10" 42" 44.75" 44.75" 44.75" 44.75" 44.75" 22.375" 22.375" 44.75" 44.75" 44.75" 44.75" 44.75" 42" 10"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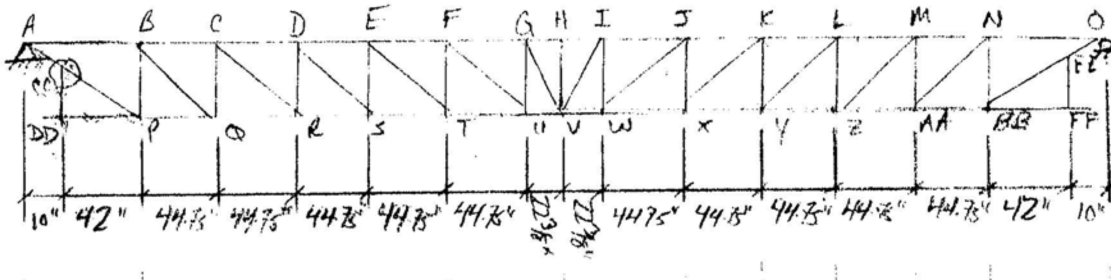
QR 0 2.84569 2.65926 0
CR 0 1.44734 -0.348887 0
CD 0 -2.54917 -3.88934 0
RD 0 -0.762683 0
RS 0 3.88934 3.5066 0
DS 0 1.30491 -0.450355 0


A B C D E F G H I J K L M N O
CC EE
DD P Q R S T U V W X Y Z AA BB FF
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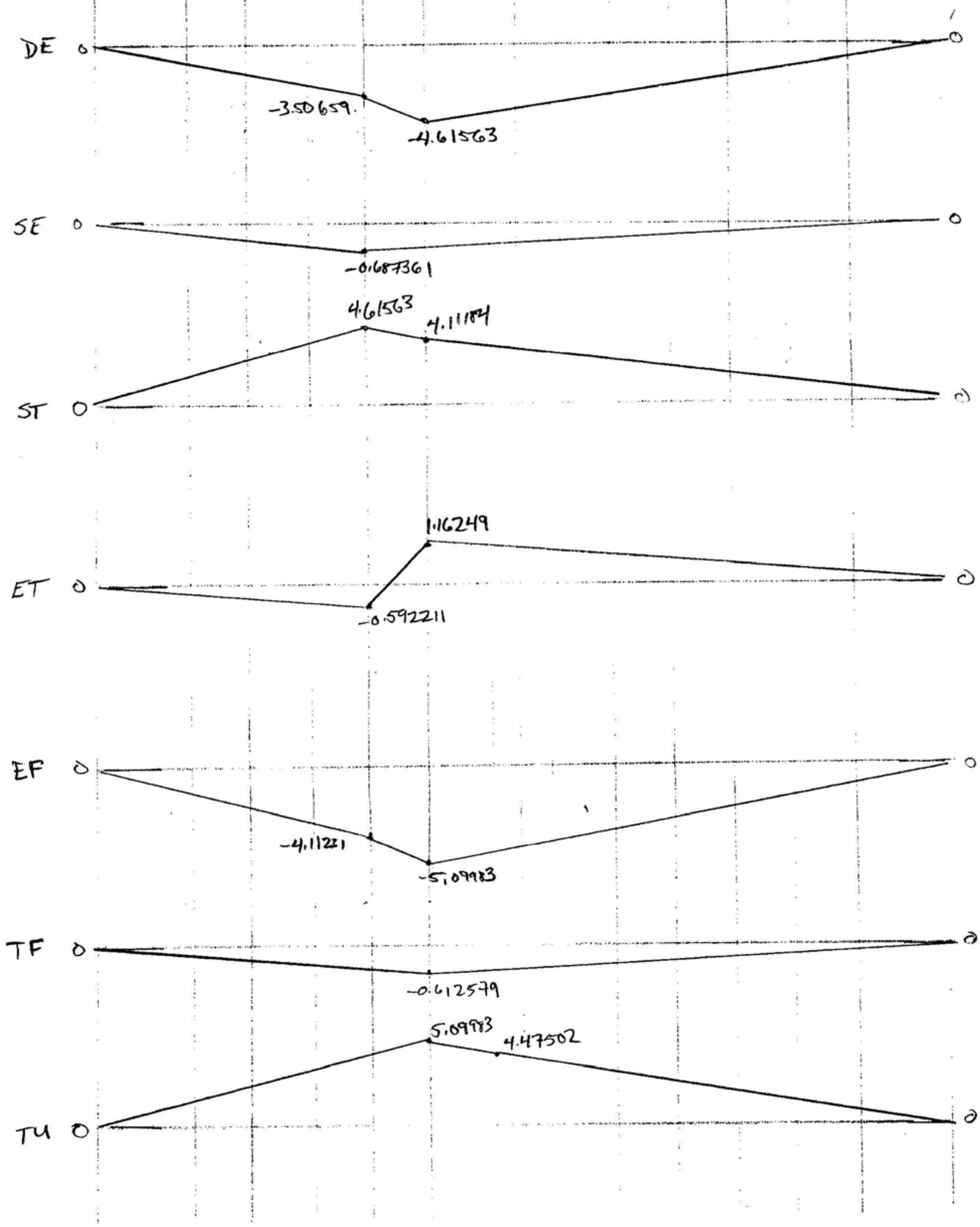
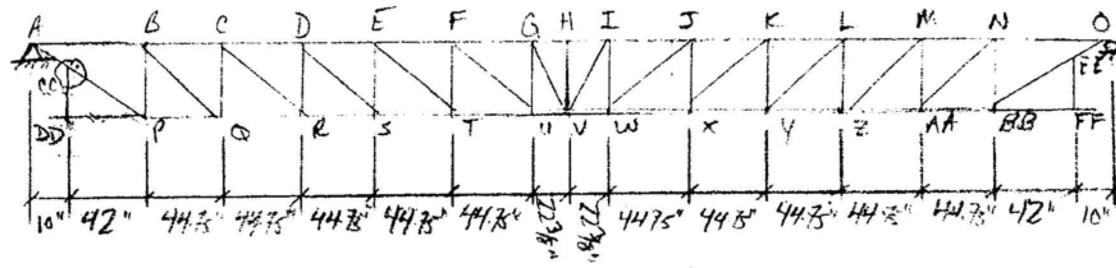
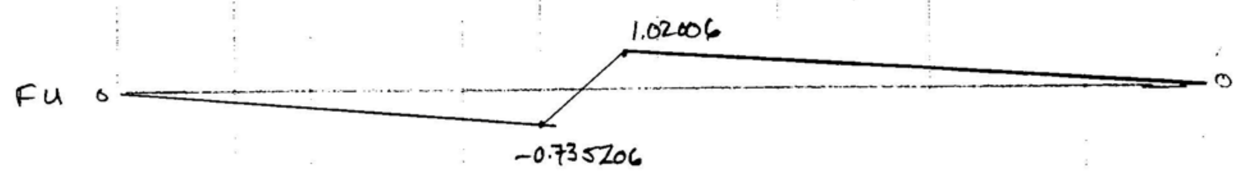
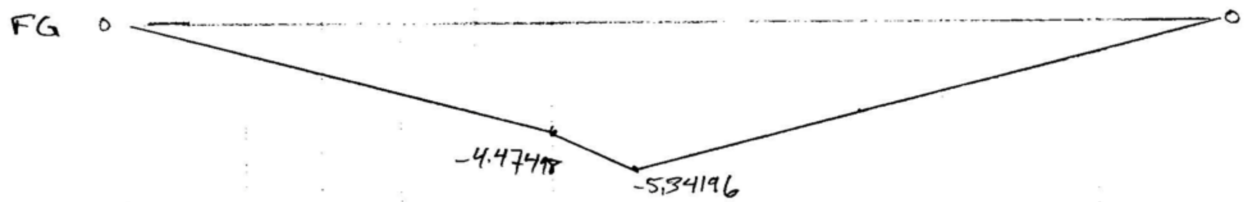
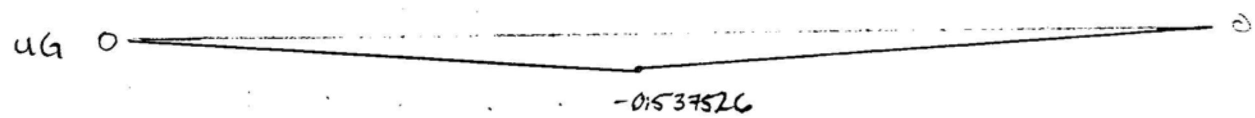

DE 0
-3.50659
-4.61563
0
SE 0
-0.687361
0
4.61563
4.11184
ST 0
0
1.16249
ET 0
-0.592211
0
EF 0
-4.11231
-5.09983
0
TF 0
-0.612579
0
5.09983
4.47502
TU 0
0

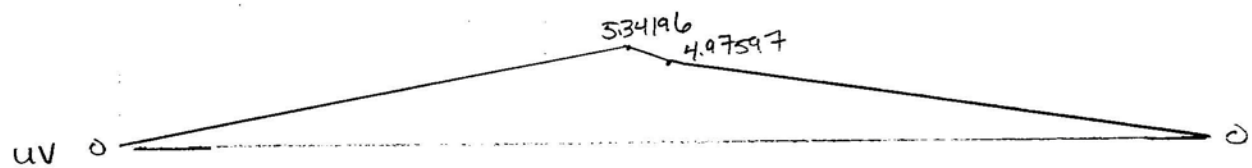
WCUW 11-11-10 4

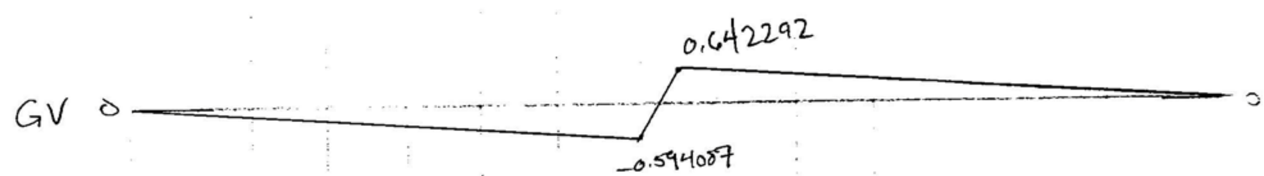


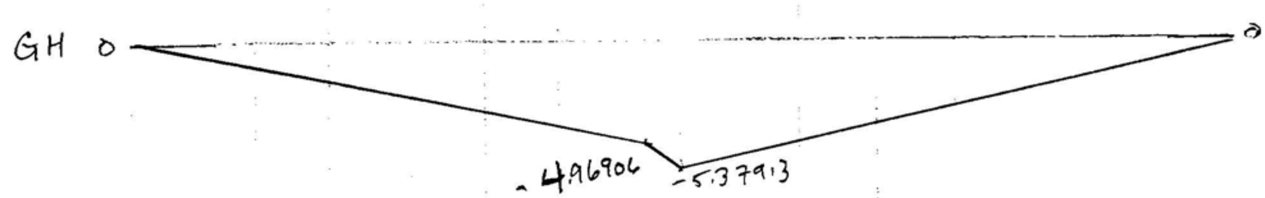


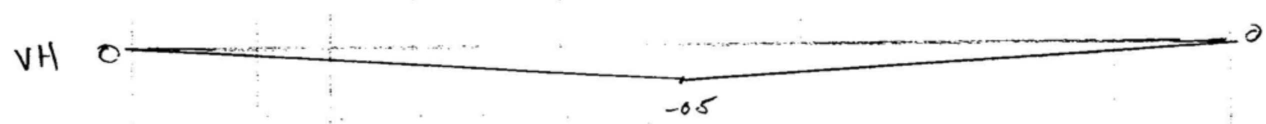


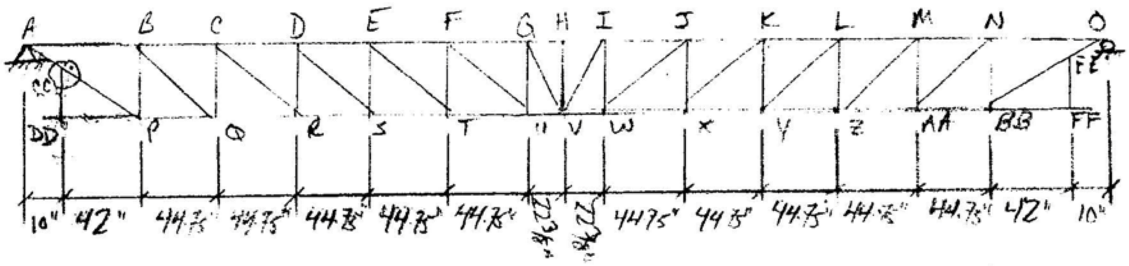


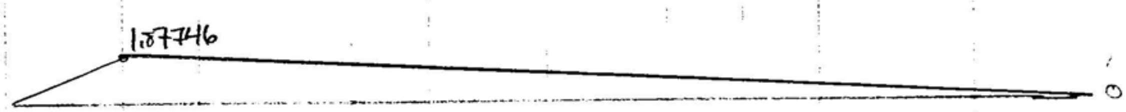


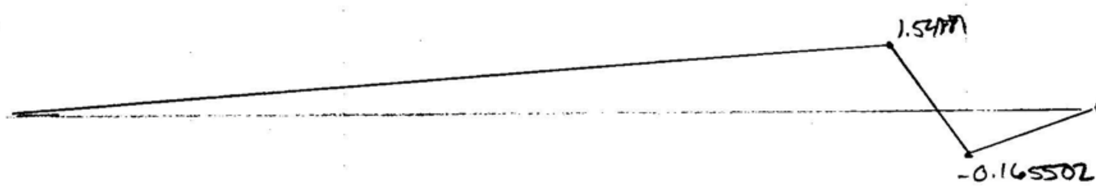






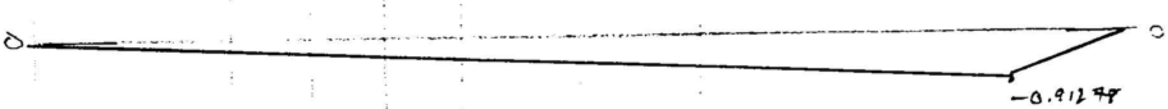


AP 0


N-AA 0


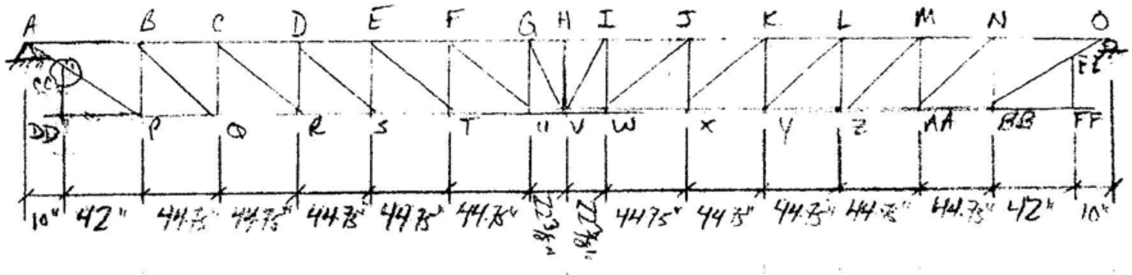
NM 0

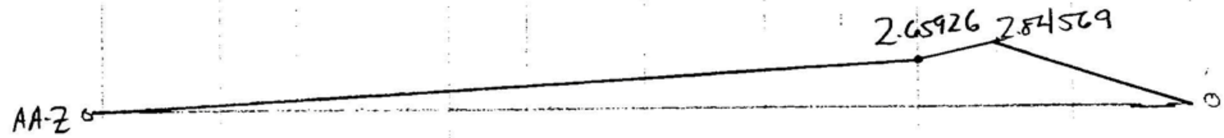

BB-AA 0

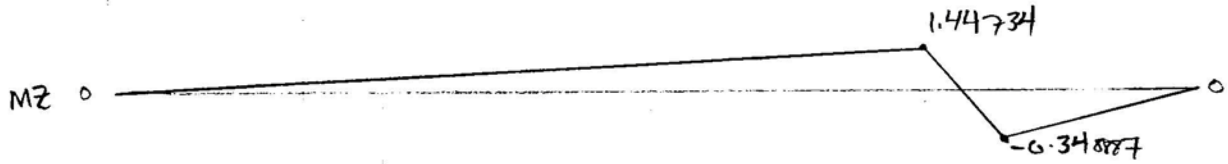

BB-N 0


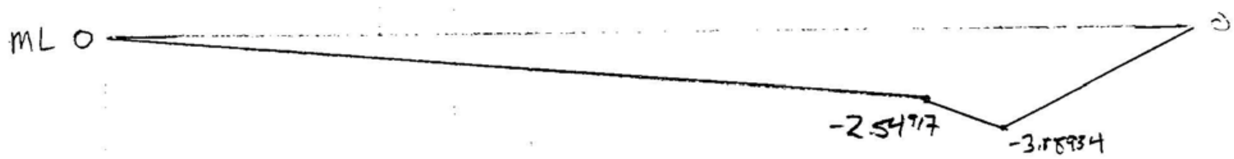
GN 0


AA-M 0

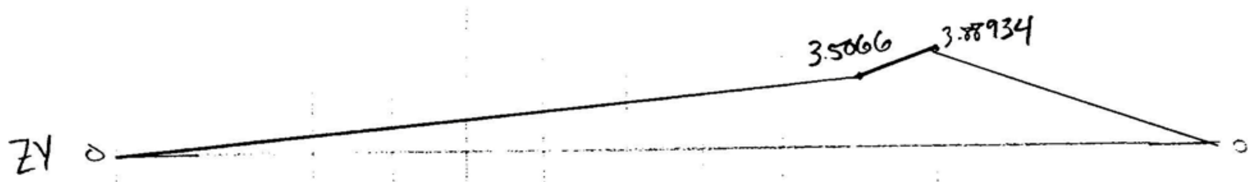


A B C D E F G H I J K L M N O
CC
DD P Q R S T U V W X Y Z AA BB FF
EE
10" 42" 44.75" 44.75" 44.75" 44.75" 44.75" 22.375" 22.375" 44.75" 44.75" 44.75" 44.75" 44.75" 42" 10"


AA-Z 0
2.65926 2.84569
0


MZ 0
1.44734
-0.348887
0


ML 0
-2.54917
-3.18934
0


ZL 0
-0.762683
0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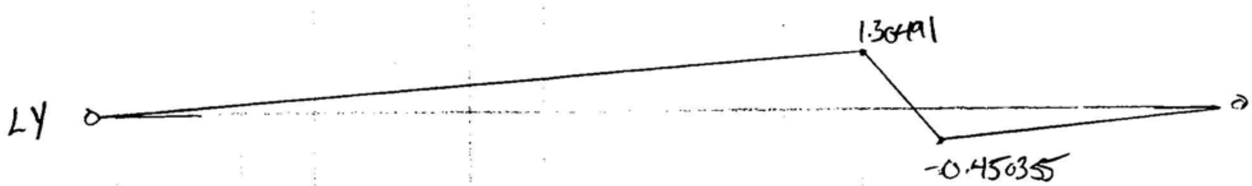
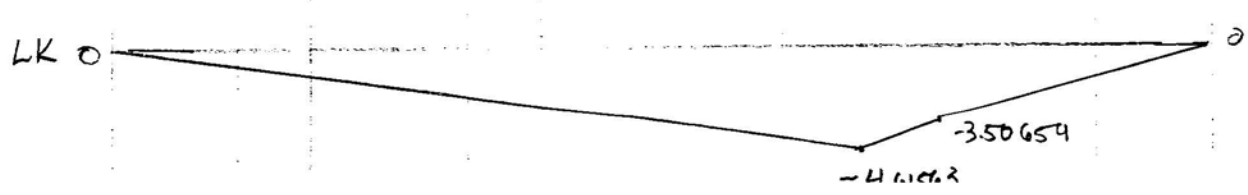
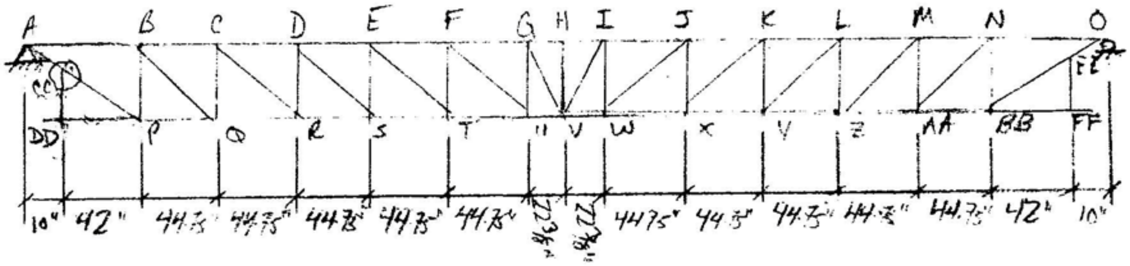
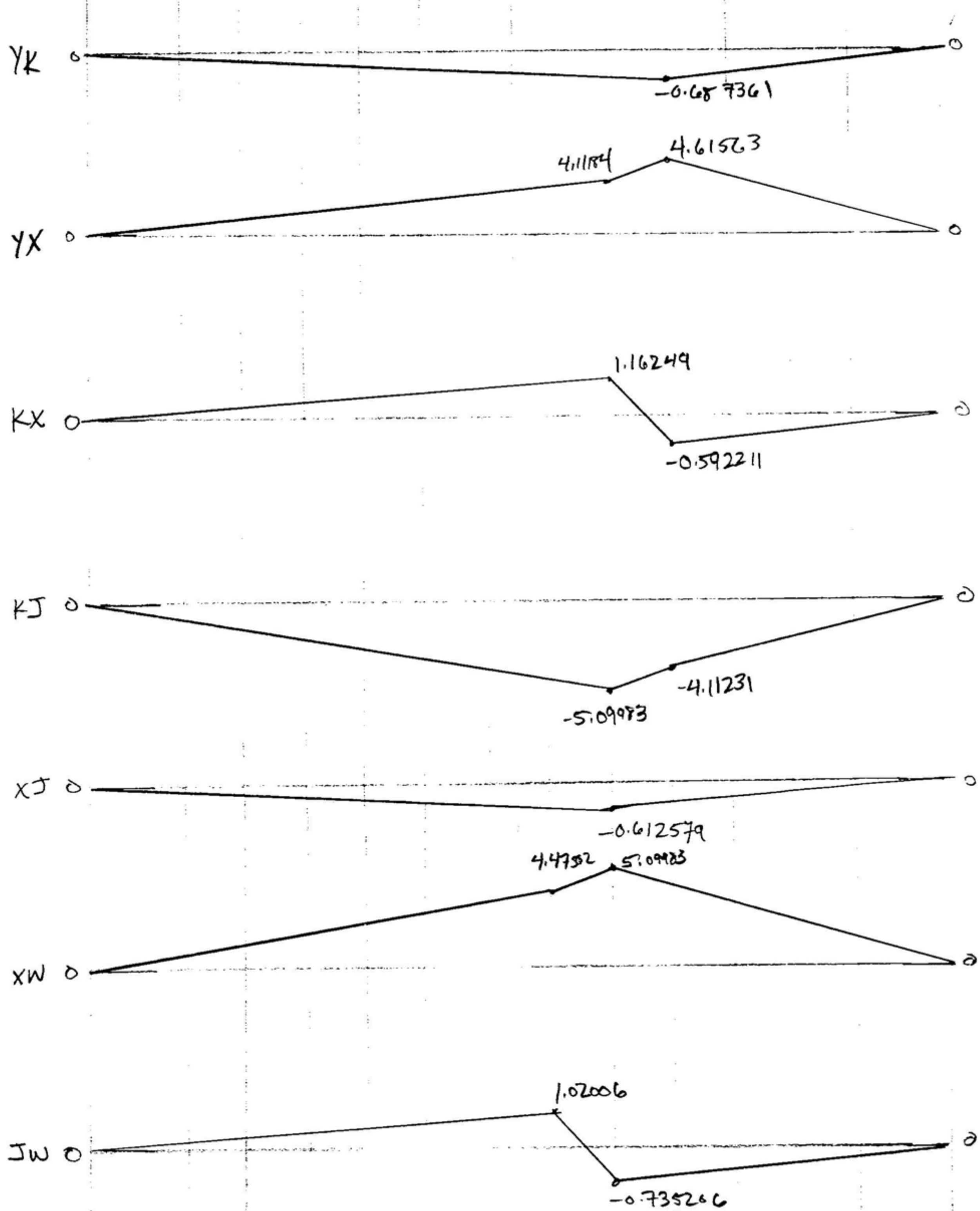
0

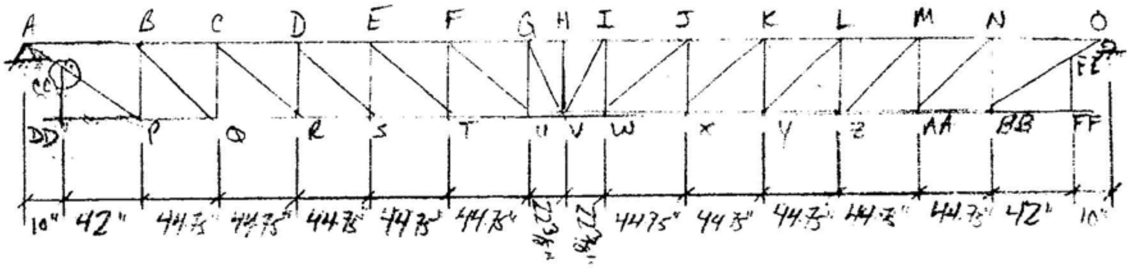

LY 0
1.30491
-0.450355
0


LK 0
-3.50654
0

WCUW 11-11-10


A B C D E F G H I J K L M N O
CC EE
DD P Q R S T U V W X Y Z AA BB FF
10" 42" 44.75" 44.75" 44.75" 44.75" 44.75" 22.375" 22.375" 44.75" 44.75" 44.75" 44.75" 44.75" 42" 10"


YK 0 -0.687361 0
YX 0 4.11184 4.61563 0
KX 0 1.16249 -0.592211 0
KJ 0 -5.09983 -4.11231 0
XJ 0 -0.612579 0
XW 0 4.47552 5.09983 0
JW 0 1.02006 -0.735206 0


A B C D E F G H I J K L M N O
CC EE
DD P Q R S T U V W X Y Z AA BB FF
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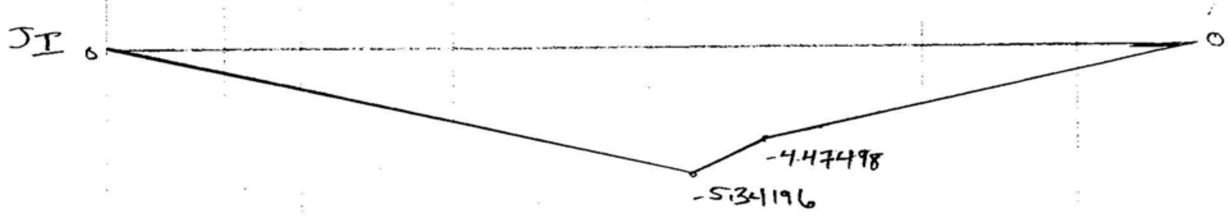
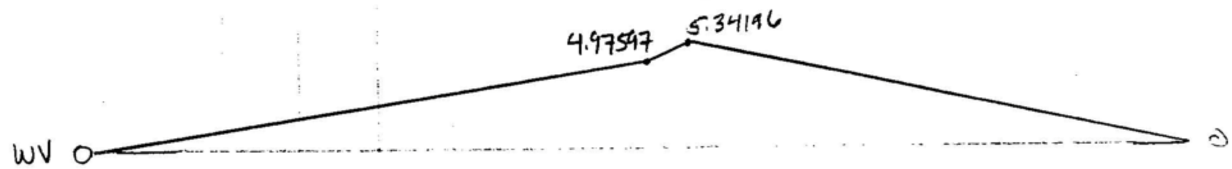

JI
0
0
-4.47498
-5.34196


WI
0
0
-0.537526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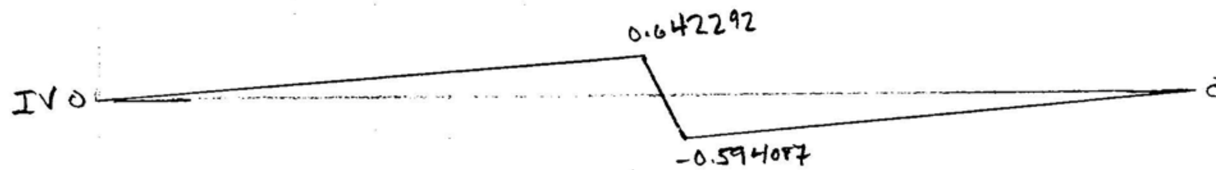
5.34196
WV
0
0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IV
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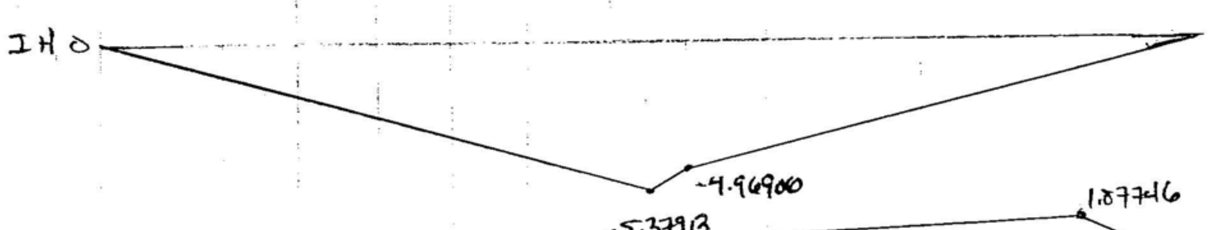
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0
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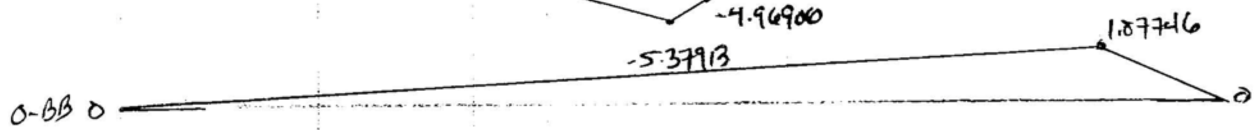
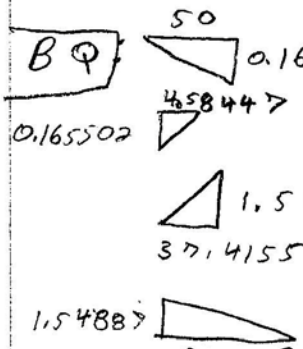
-5.37913


1.87746
O-BB
0
0

0 0

Area Under Influence Lines

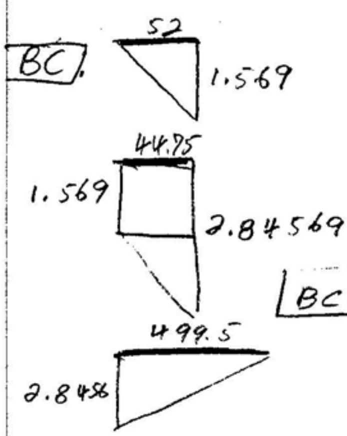
BQ



- 4.13755
- 0.37936
+ 28.97475
+ 421.4860488

$\boxed{BQ = 445.944 \text{ in}^2}$

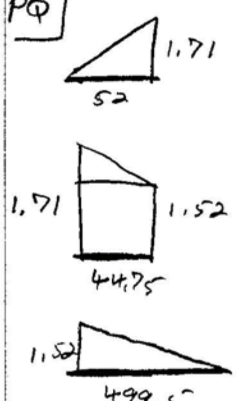
BC



- 40.794
- 70.01275
- 28.56594
- 710.6886

$\boxed{BC = -850.26129 \text{ in}^2}$

PQ



+ 44.46
+ 4.25125
+ 68.02
+ 379.62

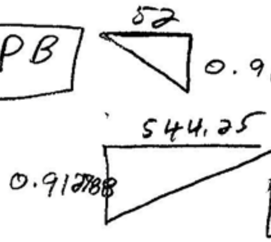
$\boxed{PQ = 496.35125 \text{ in}^2}$

AP

$A = (1.87476)(596.25)(1/2)$

$A = 558.913$

PB

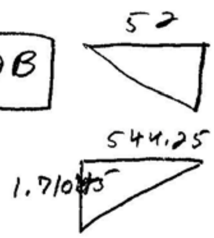


− 23.73248

− 248.3924345

$\boxed{PB = -272.1249145 \text{ in}^2}$

AB

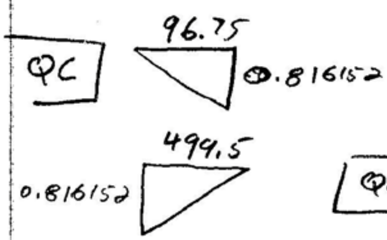


− 44.4717

− 465.45621

$\boxed{AB = -509.9279063 \text{ in}^2}$

QC

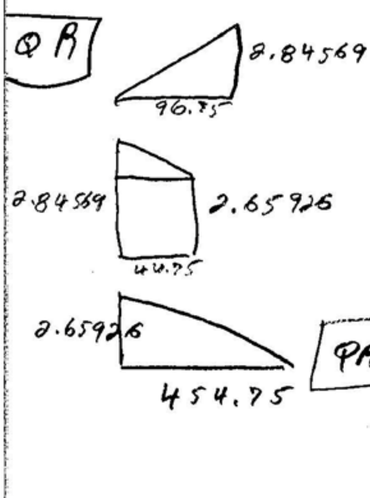


− 39.481353

− 203.833962

$\boxed{QC = -243.315315 \text{ in}^2}$

QR



+ 137.6602538

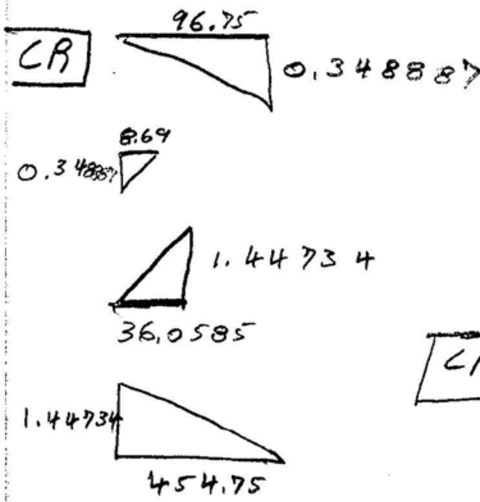
+ 4.17137125

+ 119.001885

+ 604.6492425

$\boxed{QR = 865.4827526 \text{ in}^2}$

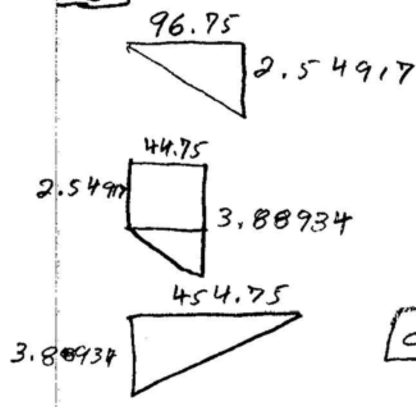
CB



- 16.87659
- 1.515914
+ 26.0944547
+ 329.0889325

$\boxed{CB = 336.7908832 \text{ in}^2}$

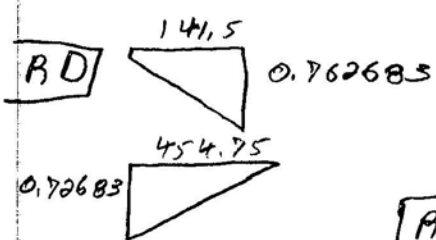
CD



- 123.3160988
- 114.0753575
- 29.9863037 5
- 884.3386825

$\boxed{CD = -1151.716443 \text{ in}^2}$

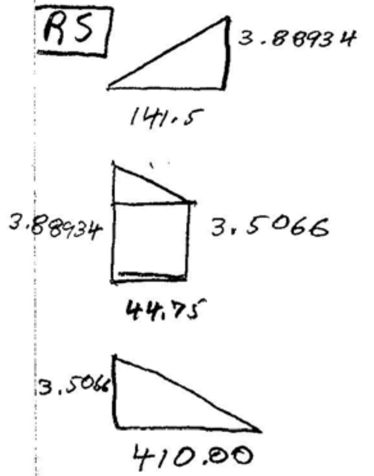
BD



- 53.9598
- 165.2629713

$\boxed{BD = -219.2227713 \text{ in}^2}$

RS



+275.170805

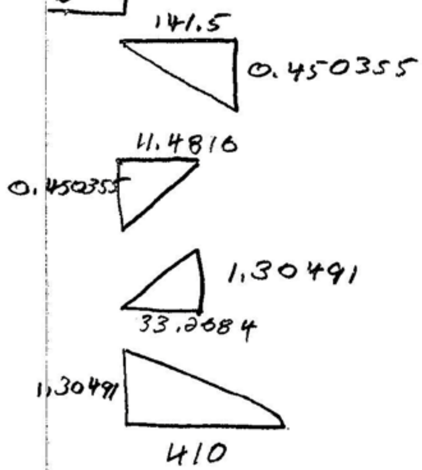
+8.5638

+156.92035

+718.853

$\boxed{RS = 1159.507955 \text{ in}^2}$

DS



−

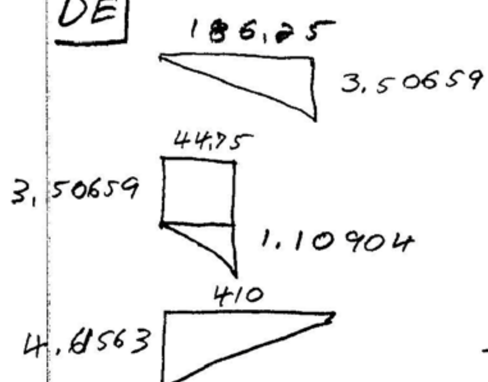
−

+

+

$\boxed{DS = 254.7646697 \text{ in}^2}$

DE



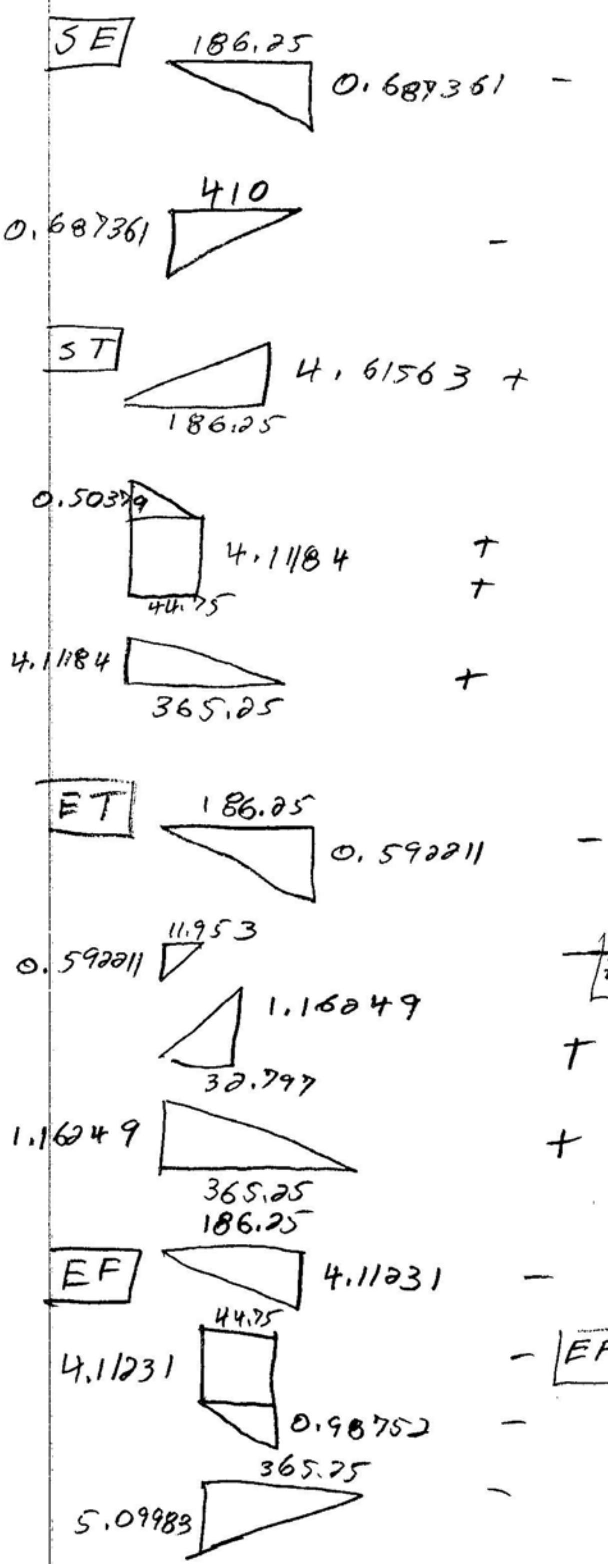
−

−

−

−

$\boxed{DE = -1454.490016 \text{ in}^2}$



$\boxed{SE = -204.919498 \ in^2}$

$\boxed{ST = 1376.032465 \ in^2}$

$\boxed{ET = 154.1919828 \ in^2}$

$\boxed{EF = -1520.436955 \ in^2}$

WCUGV

TF

231

0.612579 −

365.25

0.612579 −

TF = −182.625144 in²

TU

5.09983 +

231

0.62481

5.09983

4.47502 +

+

44.75

TU = 1369.982274 in²

4.47502 +

320.5

FU

231

−0.735206 −

18.74

0.735206 −

FU = 84.9253 in²

1.02006 +

26.01

1.02006 +

320.5

FG

231

4.47498 −

44.75

4.47498

FG = −1592.563313 in²

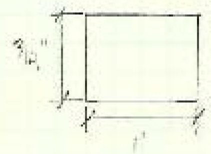
0.86698 −

320.5

5.34196 −

WCUW Radio 1

Diagonal Cross Braces:



Moment of Inertia, I:

$I = \frac{1}{12} bh^3$

$I = (\frac{1}{12})(1)(\frac{3}{4})^3$

$I = 0.035156$

Radius of gyration, r:

$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{0.035156}{(1)(3/4)}} = \sqrt{0.046875} = 0.216506$

Long Members:

$\sigma_e = \frac{\pi^2 E}{(L/r)^2} = \frac{\pi^2 (29 \times 10^6)}{(52.25/0.216506)^2} = 4914.26 \text{ psi}$

$\sigma_{cr} = (0.658^{F_y/F_e})\,\sigma_y$

$\sigma_{cr} = (0.658^{35000/4914.26})\,35000$

$\sigma_{cr} = 1105.77$ psi

$\sigma_{all} = \sigma_{cr} / F.S.$

$\sigma_{all} = 1105.77 / 1.67$

$\sigma_{all} = 662.138$ psi

Short Members:

$\sigma_e = \frac{\pi^2 E}{(L/r)^2} = \frac{\pi^2 (29 \times 10^6)}{(35.65/0.216506)^2} = 10556.5 \text{ psi}$

$\sigma_{cr} = (0.658^{F_y/F_e})\,\sigma_y$

$\sigma_{cr} = (0.658^{35000/10556.5})\,35000$

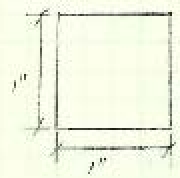
$\sigma_{cr} = 8737.7$ psi

$\sigma_{all} = \sigma_{cr} / F.S.$

$\sigma_{all} = 8737.7 / 1.67$

$\sigma_{all} = 5232.16$ psi

W2x10 Radio | | | 2



Moment of Inertia, I

$I = \frac{1}{12} bh^3$

$I = (\frac{1}{12})(1)(1)^3$

$I = 0.0833\ in^4$

Radius of gyration, r

$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{0.0833}{1}} = 0.288675\ in.$

$\sigma_e = \frac{\pi^2 E}{(L/r)^2} = \frac{\pi^2 (2.9 \times 10^7)}{(57/0.288675)^2} = 6849.16\ psi$

$\sigma_{cr} = (0.658^{\sigma_y/\sigma_e})\sigma_y$

$\sigma_{cr} = (0.658^{3500/6849.16})\ 35000$

$\sigma_{cr} = 4122.7\ psi$

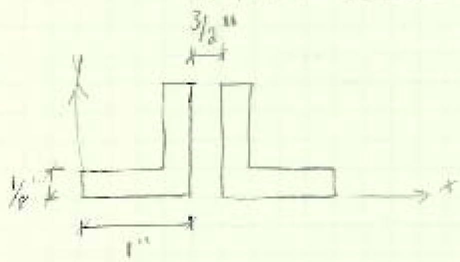
$\sigma_{all} = \sigma_{cr} / F.S.$

$\sigma_{all} = 4122.7 / 1.67$

$\sigma_{all} = 2468.68\ psi$

WCUW Radio 3

Vertical Double Angle Beams



$A = t(2a - t)$ t = thickness, a = length

$A = (1/8)(2\cdot 1 - 1/8)$

$A = 0.2344$

Due to symmetry $C_x = 7/2 - 1/2$

$C_x = 7/4$

$$C_y = \frac{a^2 + at - t^2}{2(2a - t)} = \frac{1^2 + 1\cdot 1/8 - 1/8^2}{2(2\cdot 1 - 1/8)}$$

$C_y = 0.2958$

$I = \Sigma\, 1/12\, bh^3 + Ad^2$

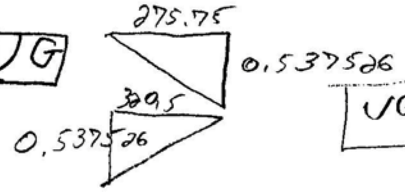
$$I_x = \left[1/12\cdot 1\cdot 1/8^3 + (1\times 1/8)(0.2958 - 1/16)^2\right]\cdot 2 + 2\cdot\left[1/12\cdot 1/8\cdot 1^3 + (1\times 1/8)(9/16 - 0.2958)^2\right]$$

$I_x = 0.052548$

$R_x = \sqrt{I_x / A}$

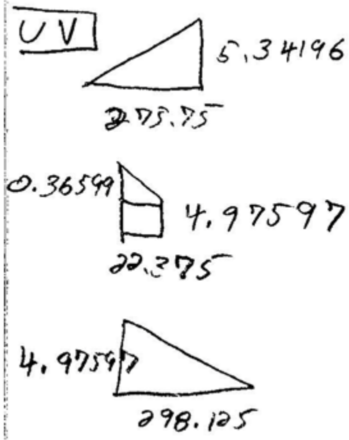
$R_x = \sqrt{0.052548 / 0.2344}$

UG



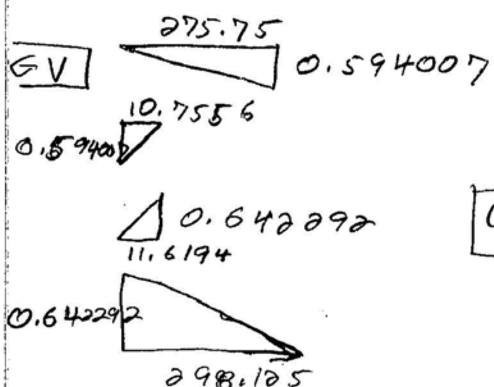
UG = −160.2499388 in²

UV



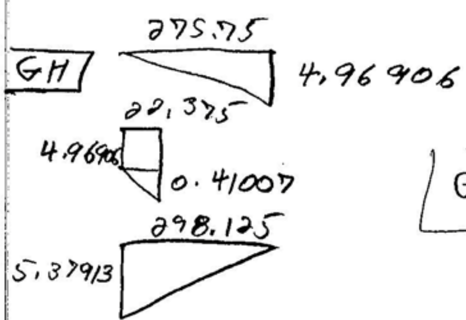
UV = 1593.685105 in²

GV



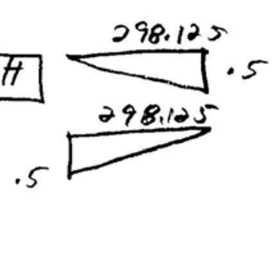
GV = 14.380 in²

GH



GH = −4474.798025 in²

VH



VH = −149.0625 in²

WCUW Radio Building, 910 Main St

Member	Dimensions (in)	A(in^2)	R_x(in)	Length (in)	Euler's (psi)	Critical Stress (psi)	Allowable Stress (psi)	Allowable Force (lb)	Area Under Influence Line (in.)	Allowable Dead Load (lb/ft)	Axial Stress (ANSYS)
AB	3x3x1/4	2.87	0.926	52	90,763.72	29,783.31	17,834.32	51,184.49	-509.93	-1,204.51	-9303.8
BC	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-850.26	-753.27	-15894
CD	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-1,151.72	-556.11	-21165
DE	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-1,454.49	-440.34	-25114
EF	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-1,520.44	-421.24	-27744
FG	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-1,592.56	-402.17	-29053
GH	3x3x1/4	2.87	0.926	22 3/8	490,222.11	33,969.57	20,341.06	58,378.84	-4,474.80	-156.55	-29215
HI	3x3x1/4	2.87	0.926	22 3/8	490,222.11	33,969.57	20,341.06	58,378.84	-4,474.80	-156.55	-29215
IJ	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-1,592.56	-402.17	-29053
JK	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-1,520.44	-421.24	-27744
KL	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-1,454.49	-440.34	-25114
LM	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-1,151.72	-556.11	-21165
MN	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	-850.26	-753.27	-15894
NO	3x3x1/4	2.87	0.926	52	90,763.72	29,783.31	17,834.32	51,184.49	-509.93	-1,204.51	-9303.8
PQ	3x3x1/4	2.87	0.926	44.75	122,555.53	31,056.76	18,596.86	53,372.99	496.35	1,290.37	9303.8
QR	3x3x1/4	2.87		44.75			20,958.10	60,149.75	865.48	833.98	15894
RS	3x3x1/4	2.87		44.75			20,958.10	60,149.75	1,159.51	622.50	21165
ST	3x3x1/4	2.87		44.75			20,958.10	60,149.75	1,376.03	524.55	25114
TU	3x3x1/4	2.87		44.75			20,958.10	60,149.75	1,369.98	526.87	27744
UV	3x3x1/4	2.87		22 3/8			20,958.10	60,149.75	1,593.69	452.91	29053
VW	3x3x1/4	2.87		22 3/8			20,958.10	60,149.75	1,593.69	452.91	29053
WX	3x3x1/4	2.87		44.75			20,958.10	60,149.75	1,369.98	526.87	27744
XY	3x3x1/4	2.87		44.75			20,958.10	60,149.75	1,376.03	524.55	25114
YZ	3x3x1/4	2.87		44.75			20,958.10	60,149.75	1,159.51	622.50	21165
ZAA	3x3x1/4	2.87		44.75			20,958.10	60,149.75	865.48	833.98	15894
AABB	3x3x1/4	2.87		44.75			20,958.10	60,149.75	496.35	1,454.21	9303.8
AP	1x1	1.00		59			20,958.10	20,958.10	558.91	449.98	30266
BQ	1x3/4	0.75		56.25			20,958.10	15,718.58	445.94	422.97	29676
CR	1x3/4	0.75		56.25			20,958.10	15,718.58	336.79	560.06	23730
DS	1x3/4	0.75		56.25			20,958.10	15,718.58	254.76	740.38	17785
ET	1x3/4	0.75		56.25			20,958.10	15,718.58	154.19	1,223.31	11839
FU	1x3/4	0.75		56.25			20,958.10	15,718.58	84.93	2,221.05	5893.6
GV	1x3/4	0.75		35.65			20,958.10	15,718.58	14.38	13,117.03	989.12
IV	1x3/4	0.75		35.65			20,958.10	15,718.58	14.38	13,117.03	989.12
JW	1x3/4	0.75		56.25			20,958.10	15,718.58	84.93	2,221.05	5893.6
KX	1x3/4	0.75		56.25			20,958.10	15,718.58	154.19	1,223.31	11839
LY	1x3/4	0.75		56.25			20,958.10	15,718.58	254.76	740.38	17785
MZ	1x3/4	0.75		56.25			20,958.10	15,718.58	336.79	560.06	23730
NAA	1x3/4	0.75		56.25			20,958.10	15,718.58	445.94	422.97	29676
OBB	1x1	1.00		59			20,958.10	20,958.10	558.91	449.98	30266
BP	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-272.12	**-181.40**	-61954
CQ	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-243.32	-202.87	-50998
DR	2x2x1/8	0.98	0.62	27.75	142,874.40	31,589.21	18,915.69	18,575.21	-219.22	-1,016.79	-9570.9
ES	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-204.92	-240.89	-30563
FT	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-182.63	-270.29	-20346
GU	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-160.25	-308.03	-10128
HV	2x2x1/8	0.98	0.62	27.75	142,874.40	31,589.21	18,915.69	18,575.21	-149.06	-1,495.37	-1178.6
IW	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-160.25	-308.03	-10128
JX	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-182.63	-270.29	-20346
KY	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-204.92	-240.89	-30563
LZ	2x2x1/8	0.98	0.62	27.75	142,874.40	31,589.21	18,915.69	18,575.21	-219.22	-1,016.79	-9570.9
MAA	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-243.32	-202.87	-50998
NBB	1x1x1/8	0.23	0.473	27.75	83,323.75	29,357.17	17,579.14	4,113.52	-272.12	**-181.40**	-61954
CCDD	1x1/4	0.25		22							
DDP	1x1/4	0.25		42							
BBFF	1x1/4	0.25		42							
EEFF	1x1/4	0.25		22							
	E=	3E+07									
	Yield Strengt	35000	psi								
	Factor of Saf	1.67									

Influence Lines - Calculations:

A_y: $\circlearrowright + \sum M_o = 0 = (-1)(688-x) + A_y(688)$:

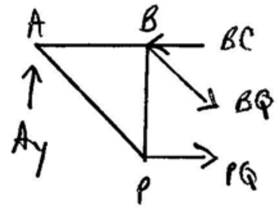
$$688A_y = 688 - x$$
$$A_y = 1 - x/688$$

x	A_y
688	0
650	0.055233
599	0.12936
548	0.203488
497	0.277616
446	0.351744
395	0.425872
344	0.5
293	0.574128
242	0.648256
191	0.722384
140	0.796512
89	0.87064
38	0.94767
0	1

D_y: $\sum F_y = 0 = -1 + A_y + D_y$

$$D_y = 1 - A_y$$

x	A_y	D_y
688	0	1
650	0.055233	0.94767
599	0.12936	0.870644
548	0.203488	0.796512
497	0.277616	0.722384
446	0.351744	0.648256
395	0.425872	0.574128
344	0.5	0.5
293	0.574128	0.425872
242	0.648256	0.351744
191	0.722384	0.277616
140	0.796512	0.203488
89	0.87064	0.12936
38	0.94767	0.055233
0	1	0



$$\Sigma F_y = 0 = A_y + BQ \sin 30.88$$
$$BQ = \frac{A_y}{\sin 30.88}$$

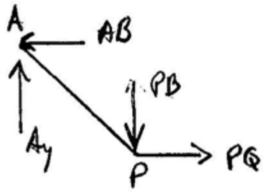
x	BQ	
0	0	
38	-0.10196	(C)
89	1.69635	(T)
140	1.55192	
191	1.40749	
242	1.26306	
293	1.11863	
344	0.9742	
688	0	

$$+\circlearrowleft \Sigma M_P = 0 = BQ\cos 30.88\,(30.5) + A_y(38) - BC(30.5)$$
$$BC = \frac{BQ\cos 30.88(30.5) + A_y(38)}{30.5}$$

x	BC	
0	0	
38	1.17783	(C)
89	3.56392	(C)
140	2.3243	
191	2.10799	
242	1.89168	
293	1.67536	
344	1.45905	
688	0	

$$\Sigma F_x = 0 = BQ\cos 30.88 - BC + PQ$$
$$PQ = BC - BQ\cos 30.88$$

X	PQ	
0	0	
38	1.26534	(T)
89	2.11349	(T)
140	0.992374	
191	0.902337	
242	0.807666	
293	0.715302	
344	0.622949	
688	0	

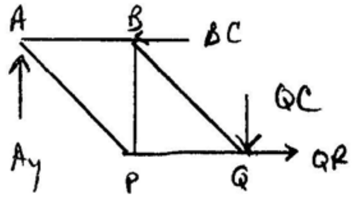


$\Sigma F_y = 0 = A_y - PB$
$PB = A_y$

x	PB
0	0
38	0.94767 (C)
688	0

$\Sigma F_x = 0 = PQ - AB$
$AB = PQ$

x	AB
0	0
38	1.26534 (C)
688	0

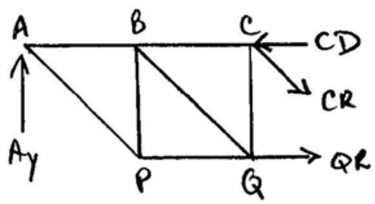


$\Sigma F_y = 0 = A_y - QC$
$QC = A_y$

x	QC
0	0
89	0.87064 (C)
688	0

$\Sigma F_x = 0 = QR - BC$
$QR = BC$

x	QR
0	0
89	3.56392 (T)
140	2.3243 (T)
191	2.10799
242	1.89168
293	1.67536
344	1.45905
688	0

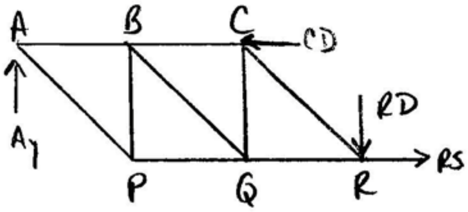


$\Sigma F_y = 0 = A_y - CR\sin 30.88$
$CR = \frac{A_y}{\sin 30.88}$

x	CR
0	0
89	-0.252045 (C)
140	1.55792 (T)
191	1.40749
242	1.26306
293	1.11863
344	0.9742
688	0

$\Sigma F_x = 0 = QR + CR\cos 30.88 - CD$
$CD = QR + CR\cos 30.88$

x	CD
0	0
89	3.3476 (C)
140	3.65623 (C)
191	3.31596
242	2.97569
293	2.63542
344	2.29515
688	0



$\Sigma F_y = 0 = A_y - RD$

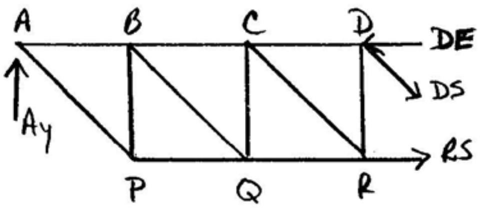
$RD = A_y$

x	RD
0	0
140	0.796572 (C)
688	0

$\Sigma F_x = 0 = RS - CD$

$RS = CD$

X	RS
0	0
140	3.65623 (T)
191	331596 (T)
242	2.97569
293	2.63542
344	2.29515
688	0



$\Sigma F_y = 0 = A_y - DS\sin 30.88$

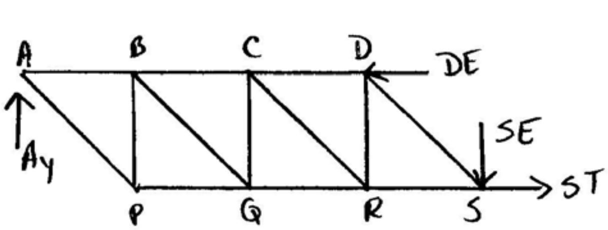
$DS = \frac{A_y}{\sin 30.88}$

X	DS
0	0
140	-0.396476 (C)
191	1.40749 (T)
242	1.26306
293	1.11863
344	0.9742
688	0

$\Sigma F_x = 0 = RS + DS\cos 30.88 - DE$

$DE = RS + DS\cos 30.88$

X	DE
0	0
140	3.31596 (C)
191	4.52393 (C)
242	4.0597
293	3.59548
344	3.13125
688	0



$\Sigma F_y = 0 = A_y - SE$

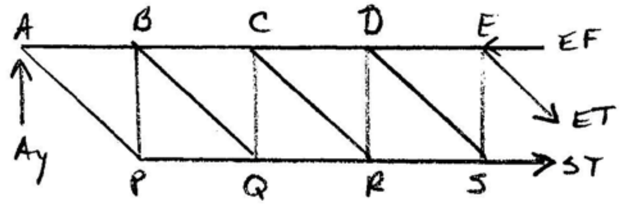
$SE = A_y$

X	SE
0	0
191	0.722384 (C)
688	0

$\Sigma F_x = 0 = ST - DE$

$ST = DE$

X	ST
0	0
191	452393 (T)
242	4.0597 (T)
293	3.59548
344	3.13125
688	0



$\Sigma F_y = 0 = A_y - ET \sin 30.88$

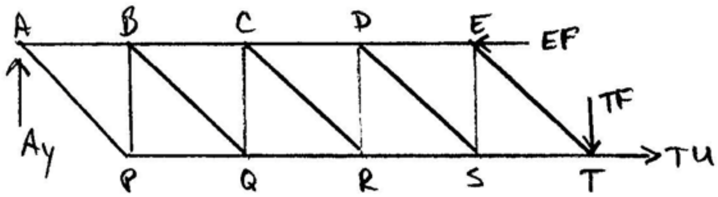
$ET = \frac{A_y}{\sin 30.88}$

X	ET	
0	0	
191	-0.540907	(C)
242	1.26306	(T)
293	1.11863	
344	0.9742	
688	0	

$\Sigma F_x = 0 = ST + ET \cos 30.88 - EF$

$EF = ST + ET \cos 30.88$

X	EF
0	0
191	4.0597 (C)
242	5.14371 (T)
293	4.55554
344	3.96735
688	0



$\Sigma F_y = 0 = A_y - TF$

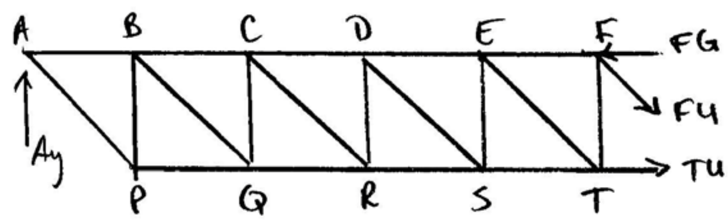
$TF = A_y$

X	TF
0	0
242	0.648256 (C)
688	0

$\Sigma F_x = 0 = TU - EF$

$TU = EF$

X	TU
0	0
242	5.14371 (T)
293	4.55554 (T)
344	3.96735
688	0



$\Sigma F_y = 0 = A_y - FU \sin 30.88$

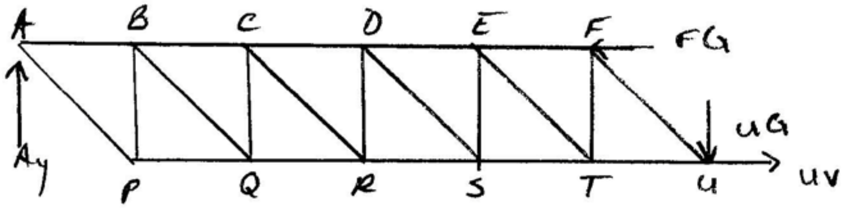
$FU = \frac{A_y}{\sin 30.88}$

X	FU	
0	0	
242	-0.68534	(C)
293	1.11863	(T)
344	0.9742	
688	0	

$\Sigma F_x = 0 = TU + FU \cos 30.88 - FG$

$FG = TU + FU \cos 30.88$

X	FG
0	0
242	4.55552 (C)
293	5.6156 (C)
344	4.80345
688	0



$\Sigma F_y = 0 = A_y - UG$

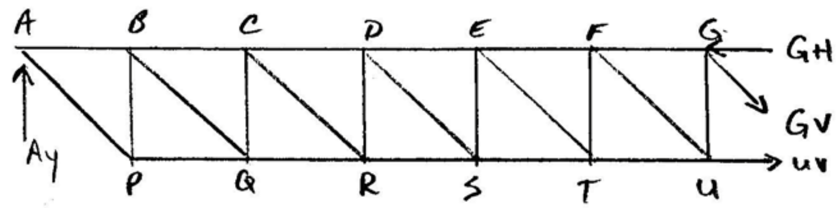
$UG = A_y$

x	UG
0	0
293	0.574128 (C)
688	0

$\Sigma F_x = 0 = UV - FG$

$UV = FG$

x	UV
0	0
293	4.55552 (T)
344	5.5156 (T)
0	0



$\Sigma F_y = 0 = A_y - GV \sin 30.88$

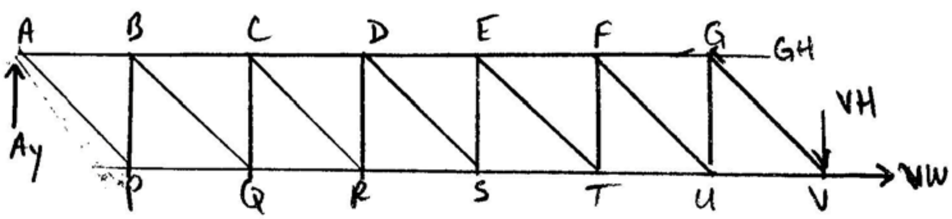
$GV = \dfrac{A_y}{\sin 30.88}$

x	GV
0	0
293	-0.829769 (C)
344	0.9742 (T)
688	0

$\Sigma F_x = 0 = UV + GV \cos 30.88 - GH$

$GH = UV + GV \cos 30.88$

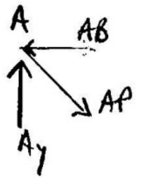
x	GH
0	0
293	3.84363 (C)
344	6.3517 (C)
688	0



$\Sigma F_y = 0 = A_y - VH$

$VH = A_y$

x	VH
0	0
344	0.5 (C)
688	0



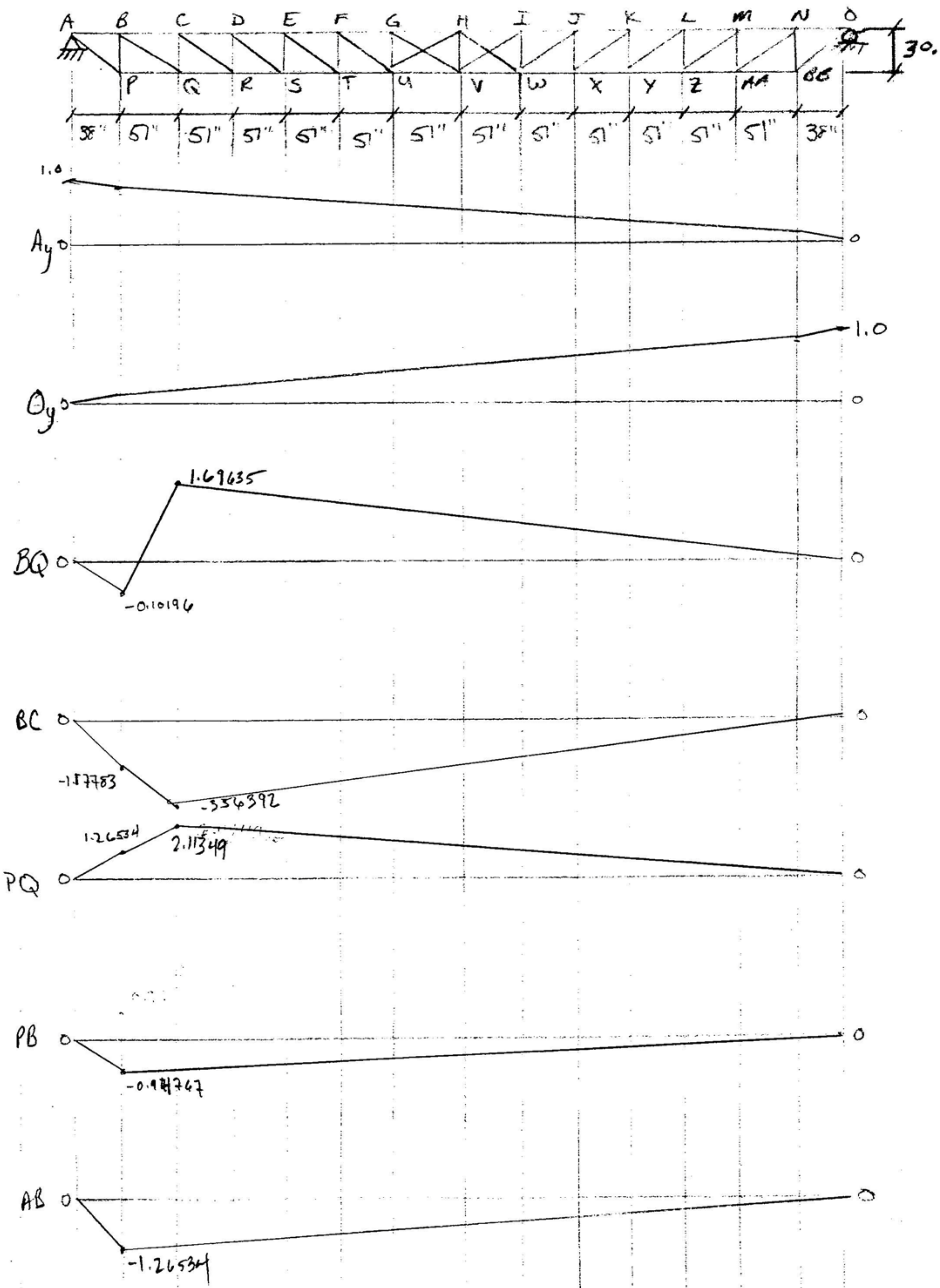
$$\Sigma F_y = 0 = A_y - AP\sin 38.75$$

$$AP = \frac{A_y}{\sin 38.75}$$

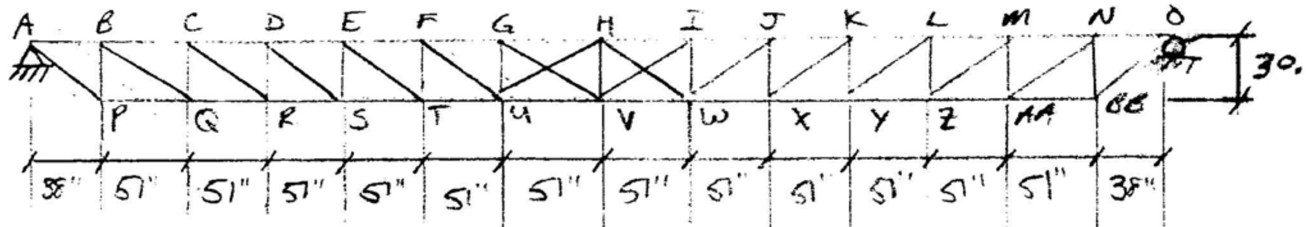
x	AP
0	0
38	1.57403 (T)
688	0

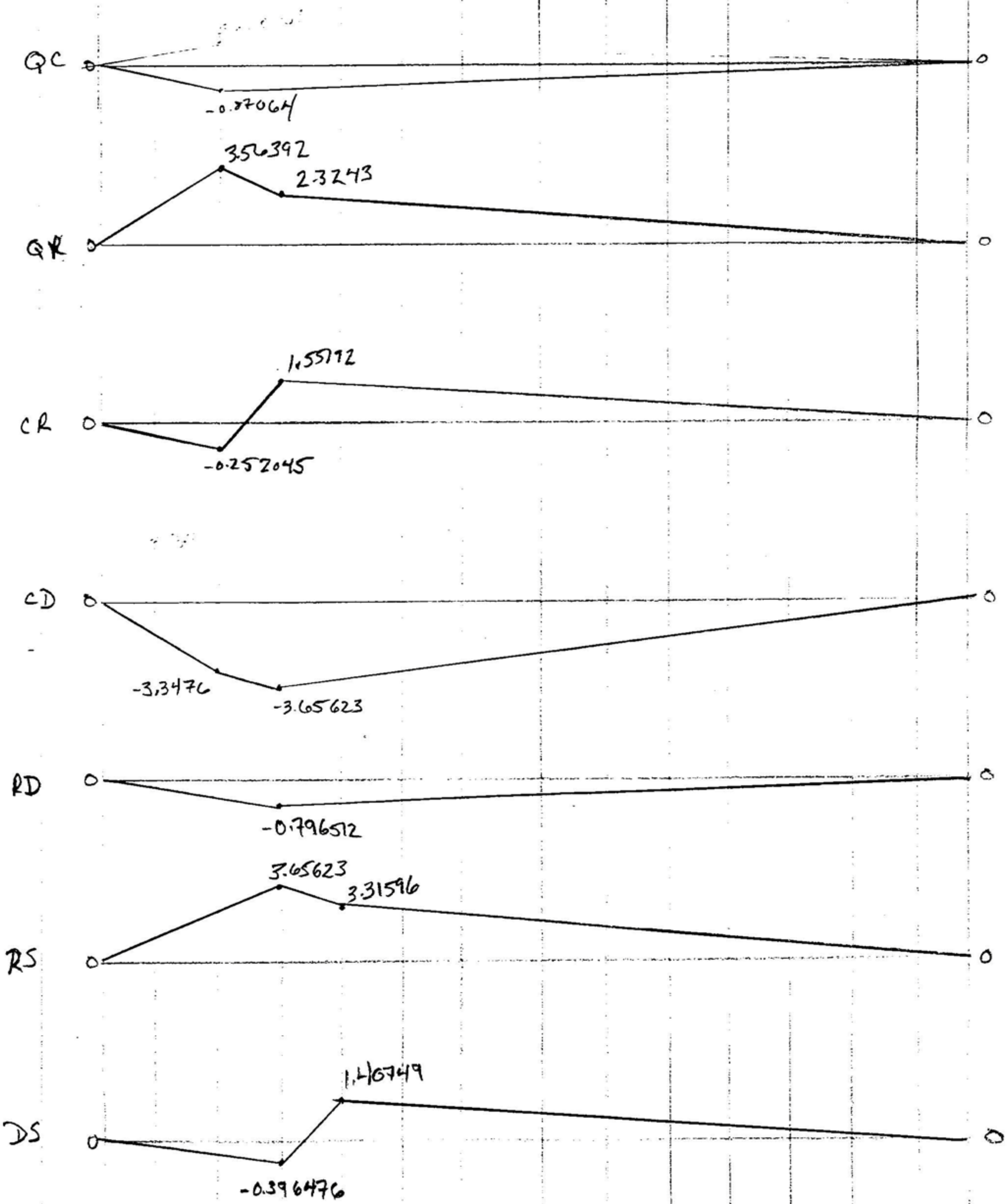
CDC Garage

11-11-10

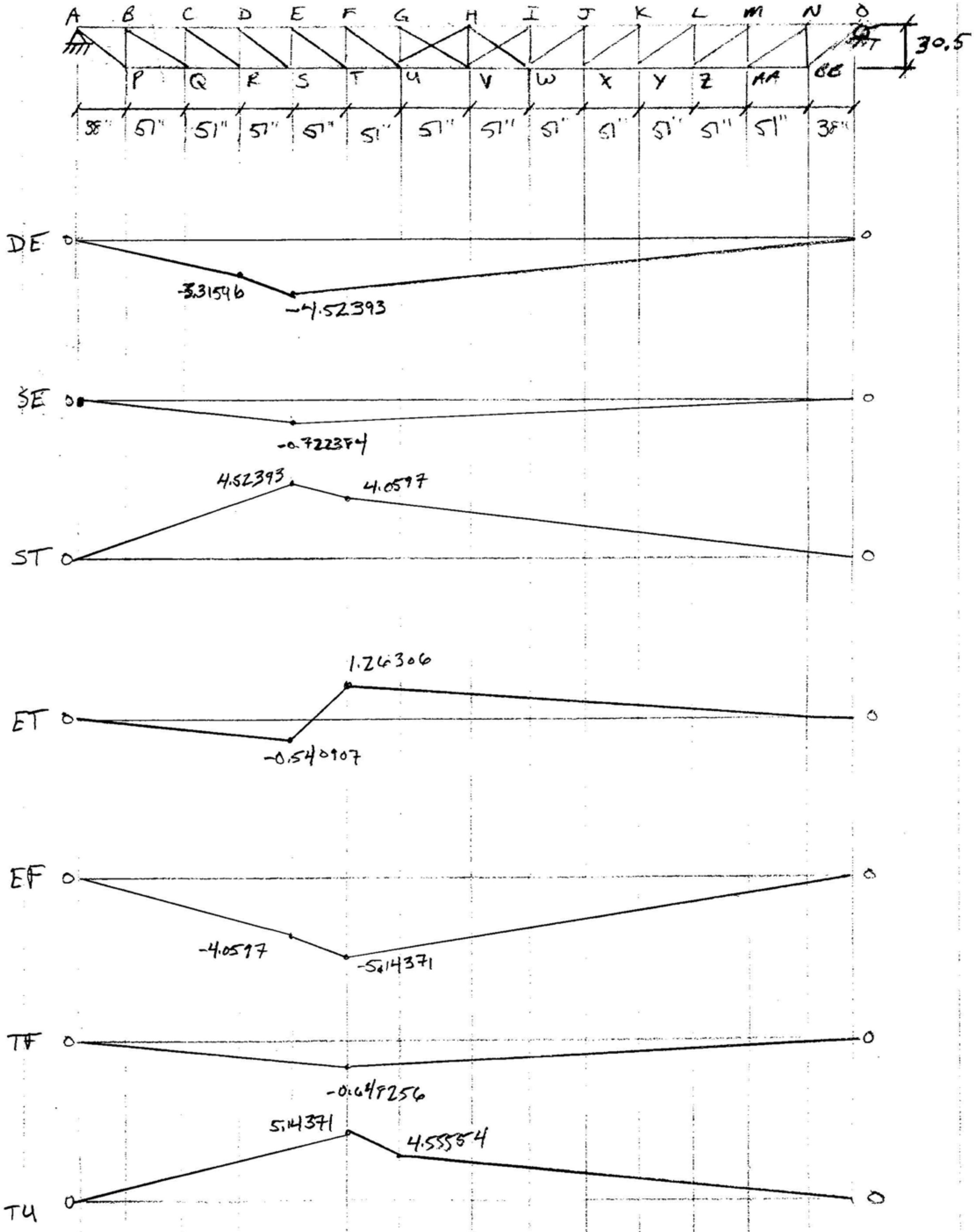


CDC Garage

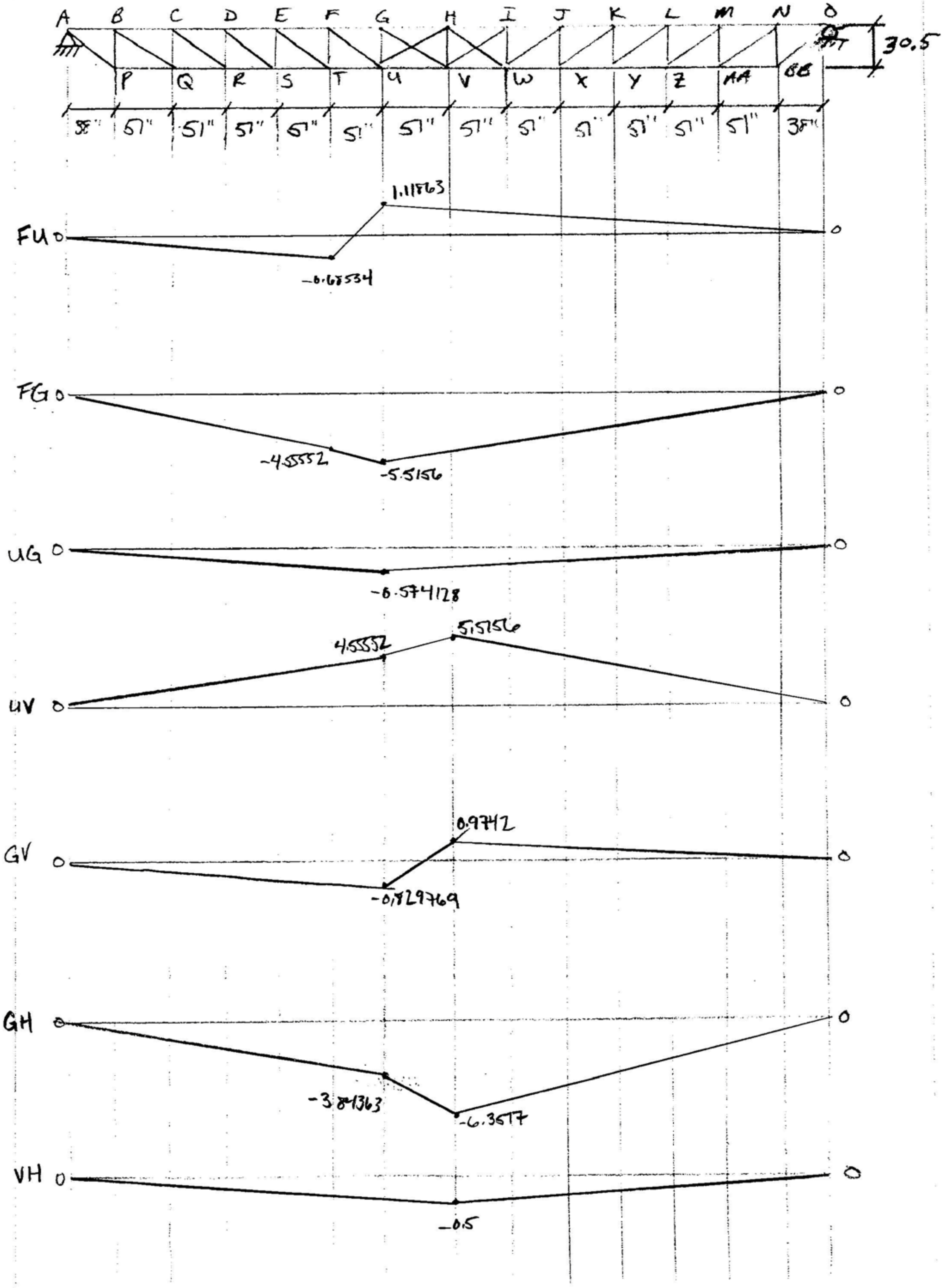

A B C D E F G H I J K L M N O
P Q R S T U V W X Y Z AA BB
30.5
38" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 38"

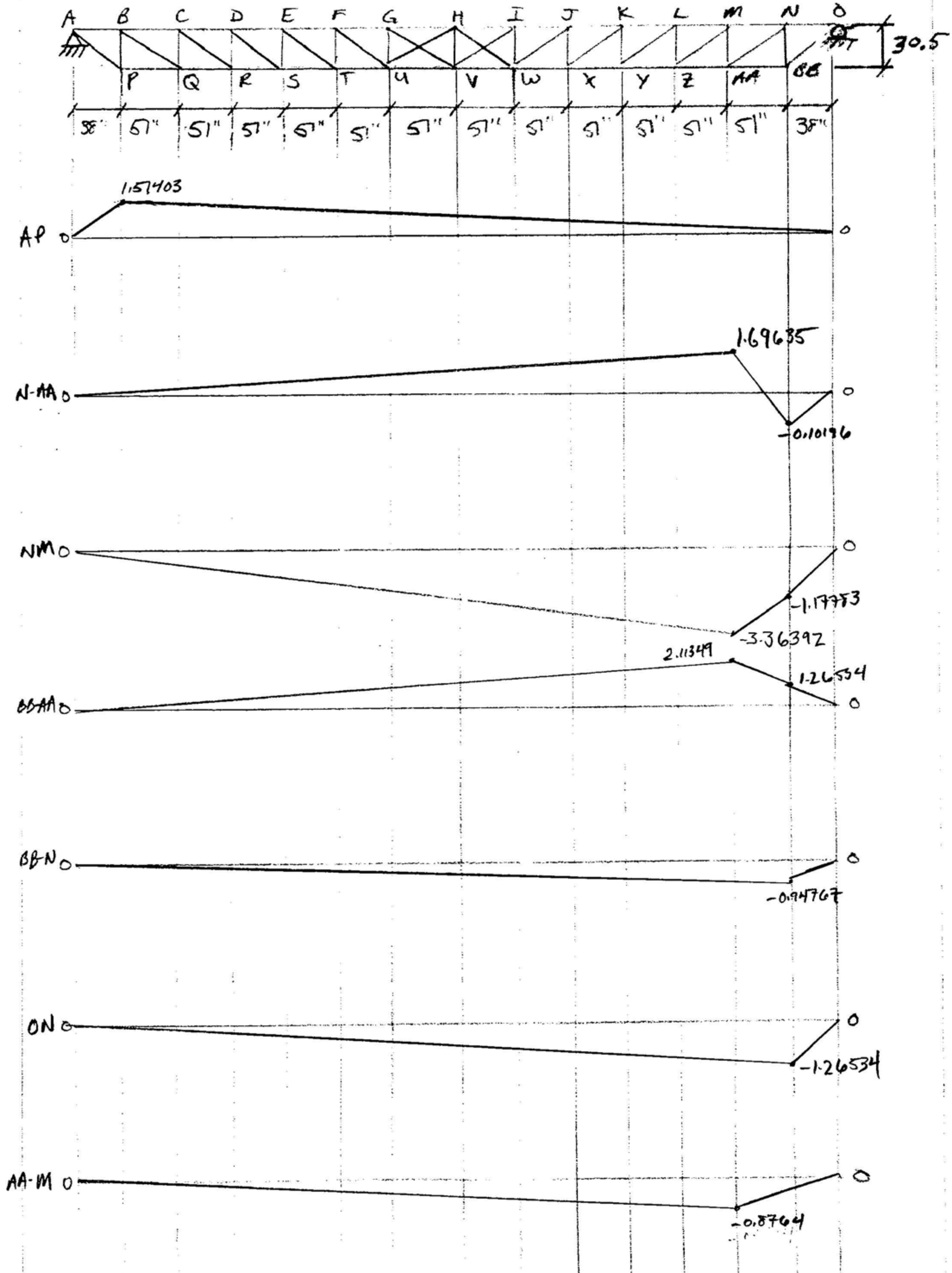

QC
0
-0.87064
0
QR
0
3.56392
2.3243
0
CR
0
1.55792
-0.252045
0
CD
0
-3.3476
-3.65623
0
RD
0
-0.796512
0
RS
0
3.65623
3.31596
0
DS
0
1.46749
-0.396476
0

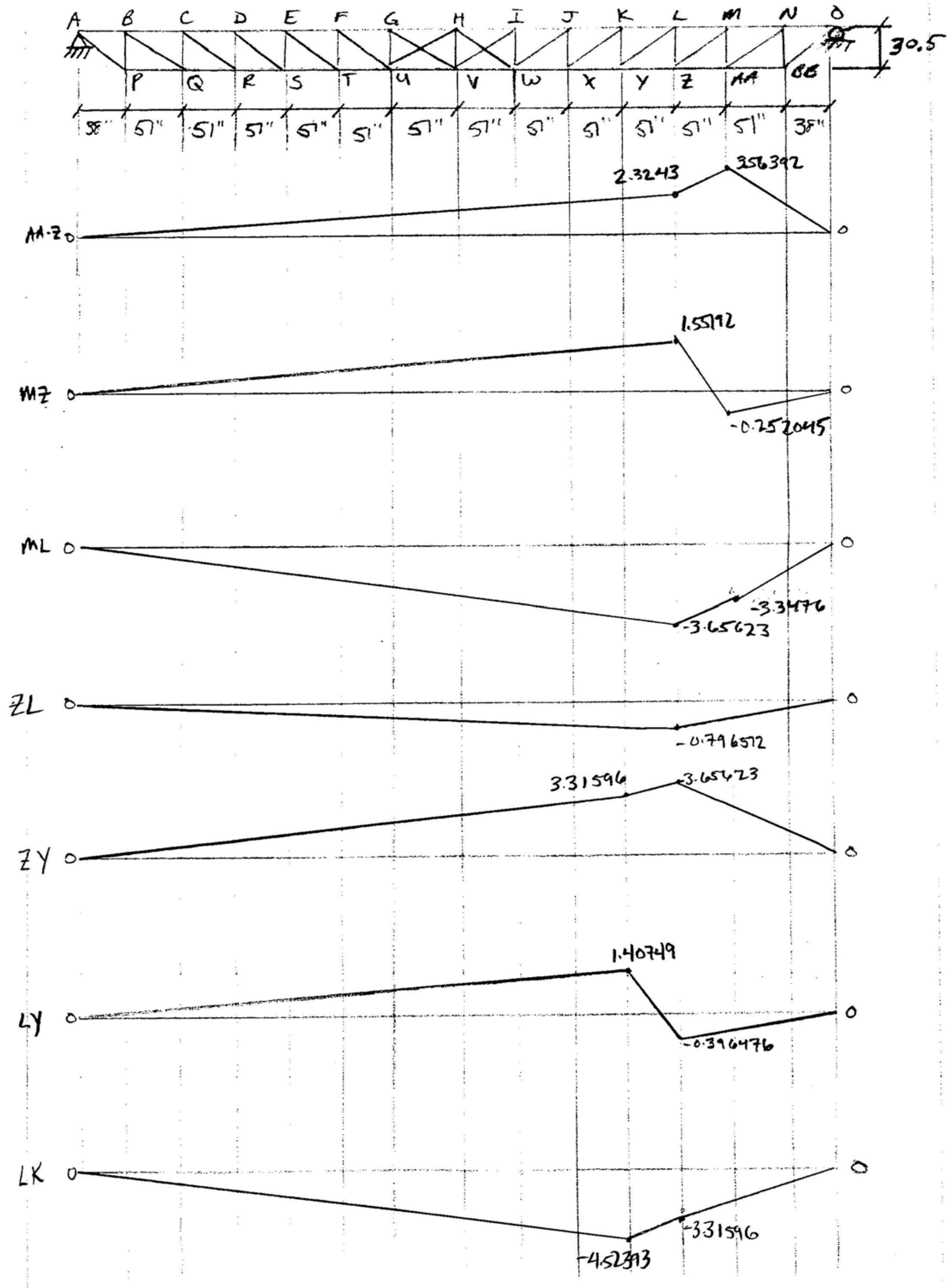
CDC Garage


A B C D E F G H I J K L M N O
P Q R S T U V W X Y Z AA BB
30.5
38" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 38"
DE 0 -3.31546 -4.52393 0
SE 0 -0.722384 0
ST 0 4.52393 4.0597 0
ET 0 1.26306 -0.540907 0
EF 0 -4.0597 -5.14371 0
TF 0 -0.648256 0
TU 0 5.14371 4.55554 0

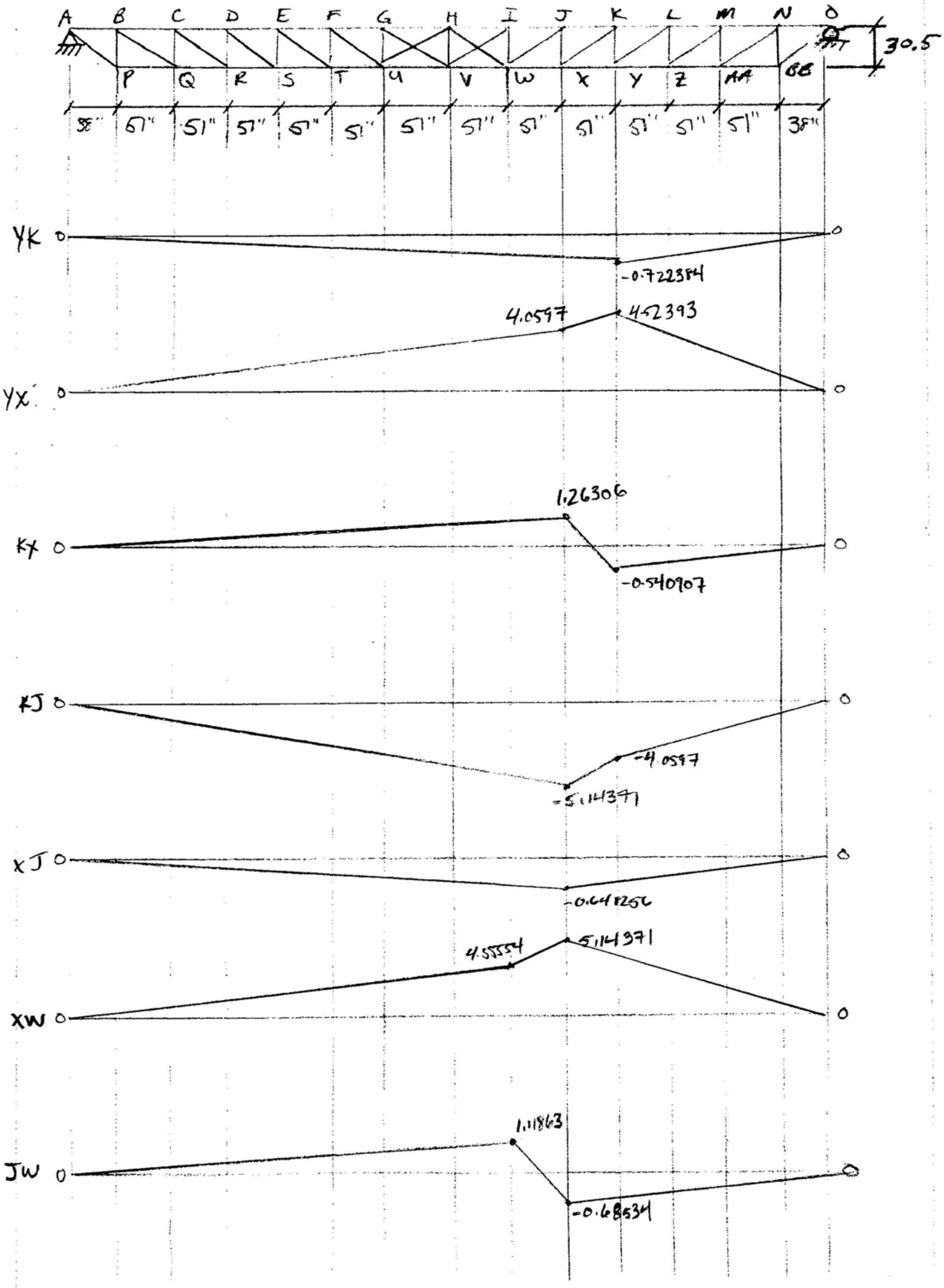
CDC Garage

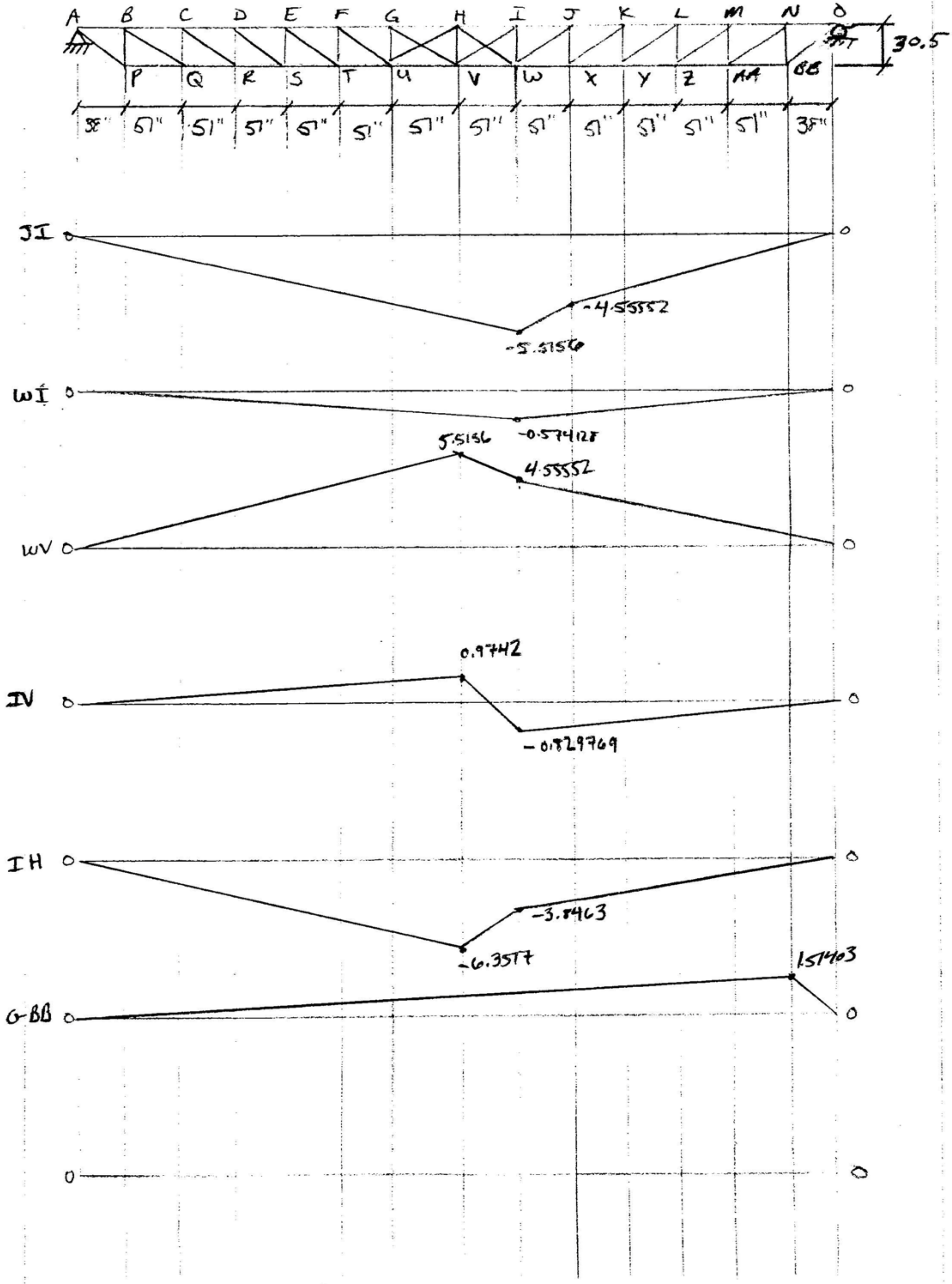

A B C D E F G H I J K L M N O
P Q R S T U V W X Y Z AA BB
30.5
38" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 38"
FU 0
1.11863
-0.68534
0
FG 0
-4.5552
-5.5156
0
UG 0
-0.574128
0
UV 0
4.5552
5.5156
0
GV 0
0.9742
-0.829769
0
GH 0
-3.81363
-6.3577
0
VH 0
-0.5
0


A B C D E F G H I J K L M N O
30.5
P Q R S T U V W X Y Z AA BB
38" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 38"
1.57403
AP 0
0
1.69635
N-AA 0
0
-0.10196
NM 0
0
-1.17783
-3.36392
2.11349
1.26534
BB-AA 0
0
BB-N 0
0
-0.94767
ON 0
0
-1.26534
AA-M 0
0
-0.8764


A B C D E F G H I J K L M N O
P Q R S T U V W X Y Z AA BB
30.5
38" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 38"
AA-Z 0
2.3243
3.56392
0
MZ 0
1.55192
-0.252045
0
ML 0
-3.65623
-3.34476
0
ZL 0
-0.796572
0
ZY 0
3.31596
3.65623
0
LY 0
1.40749
-0.396476
0
LK 0
-4.52393
-3.31596
0

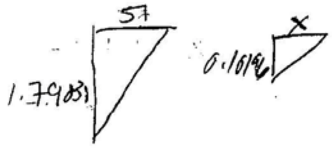
CDC Garage


A
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
X
Y
Z
AA
BB
30.5
38"
51"
38"
YK
-0.722384
YX
4.0597
4.52393
KX
1.26306
-0.540907
KJ
-5.114371
-4.0597
XJ
-0.641256
XW
4.55554
5.114371
JW
1.11863
-0.68534


A B C D E F G H I J K L M N O
P Q R S T U V W X Y Z AA BB
30.5
38" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 51" 38"
JI 0 0
-4.55552
-5.5156
WI 0 0
-0.574128
5.5156
4.55552
WV 0 0
0.9742
IV 0 0
-0.829769
IH 0 0
-3.8463
-6.3577
1.51403
G-BB 0 0
0 0

Areas Under Influence Diagrams: $A_T = \frac{1}{2} bh$ $A_r = bh$

BQ:



$$\frac{1.79831}{0.10196} = \frac{51}{x}$$

$$x = \frac{51(0.10196)}{1.79831} = 2.89158$$

$A = (1.69635)[599 + (51 - 2.89158)]/2 - (0.10196)(38 + 2.89158)/2$
$A = 544.409$ in.

BC:
$A = (1.17783)(38)(\frac{1}{2}) + (3.56392)(\frac{1}{2})(599) + (51)(1.17783) + (3.56392 - 1.17783)(51)(\frac{1}{2})$
$A = 1188.46$ in.

PQ:
$A = (1.26534)(38)(\frac{1}{2}) + (2.11349)(\frac{1}{2})(599) + (51)(1.26534) + (2.11349 - 1.26534)(51)(\frac{1}{2})$
$A = 743.192$ in.

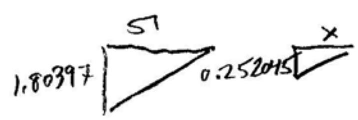
PB:
$A = (0.94767)(688)(\frac{1}{2})$
$A = 325.998$ in.

AB:
$A = (1.26534)(688)(\frac{1}{2})$
$A = 435.277$ in.

QC:
$A = (0.87064)(688)(\frac{1}{2})$
$A = 299.5$ in.

QR:
$A = (3.56392)(89)(\frac{1}{2}) + (2.3243)(548)(\frac{1}{2}) + (2.3243)(51) + (3.56392 - 2.3243)(51)(\frac{1}{2})$
$A = 945.602$ in.

CR:



$$\frac{1.80397}{0.252045} = \frac{51}{x}$$

$$x = \frac{(51)(0.252045)}{1.80397} = 7.12556$$

$A = (0.252045)(\frac{1}{2})(89 + 7.12556) + (1.55192)(\frac{1}{2})[548 + (51 - 7.12556)]$
$A = 447.157$ in.

CD:
$A = (3.3476)(89)(\frac{1}{2}) + (3.65623)(548)(\frac{1}{2}) + (3.3476)(51) + (3.65623 - 3.3476)(51)(\frac{1}{2})$
$A = 1329.37$ in.

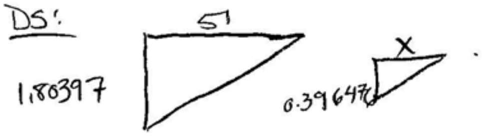
RD:
$A = (0.796512)(688)(\frac{1}{2})$
$A = 274$ in.

RS:

$A = (3.65623)(140)(\tfrac{1}{2}) + (3.31596)(497)(\tfrac{1}{2}) + (3.31596)(51) + (3.65623 - 3.31596)(51)(\tfrac{1}{2})$

$A = 1257.74$ in.

DS:



$\dfrac{1.80397}{0.396476} = \dfrac{51}{X}$

$X = \dfrac{(51)(0.396476)}{1.80397} = 11.2088$

$A = (1.40749)(\tfrac{1}{2})[497 + (51 - 11.2088)] - (0.396476)(\tfrac{1}{2})(140 + 11.2088)$

$A = 347.789$ in.

DE:

$A = (3.31596)(140)(\tfrac{1}{2}) + (4.52393)(497)(\tfrac{1}{2}) + (3.31596)(51) + (4.52393 - 3.31596)(51)(\tfrac{1}{2})$

$A = 1556.23$ in

SE:

$A = (0.722384)(\tfrac{1}{2})(688)$

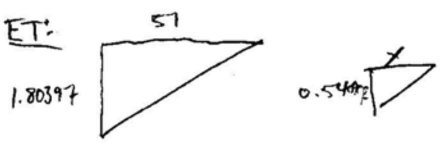
$A = 248.5$ in.

ST:

$A = (4.52393)(191)(\tfrac{1}{2}) + (4.0597)(446)(\tfrac{1}{2}) + (4.0597)(51) + (4.52393 - 4.0597)(51)(\tfrac{1}{2})$

$A = 1556.23$ in.

ET:



$\dfrac{51}{X} = \dfrac{1.80397}{0.540907}$

$X = \dfrac{(51)(0.540907)}{1.80397} = 15.292$

$A = (1.26306)(\tfrac{1}{2})[446 + (51 - 15.292)] - (0.540907)(\tfrac{1}{2})(191 + 15.292)$

$A = 248.421$

EF:

$A = (4.0597)(191)(\tfrac{1}{2}) + (5.14371)(446)(\tfrac{1}{2}) + (4.0597)(51) + (5.14371 - 4.0597)(51)(\tfrac{1}{2})$

$A = 1769.44$ in.

TF:

$A = (0.648256)(688)(\tfrac{1}{2})$

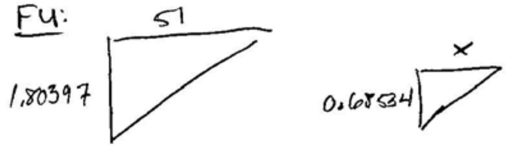
$A = 223$ in.

TU:

$A = (5.14371)(242)(\tfrac{1}{2}) + (4.55554)(395)(\tfrac{1}{2}) + (4.55554)(51) + (5.14371 - 4.55554)(51)(\tfrac{1}{2})$

$A = 1769.44$ in.

FU:



$$\frac{51}{x} = \frac{1.80397}{0.68534}$$

$$x = \frac{(51)(0.68534)}{1.80397} = 19.3752$$

$A = (1.11863)(1/2)[395 + (51 - 19.3752)] - (0.68534)(1/2)(242 + 19.3752)$

$A = 149.052$ in.

FG:

$A = (4.55552)(242)(1/2) + (5.5156)(395)(1/2) + (4.55552)(51) + (5.5796 - 4.55552)(51)(1/2)$

$A = 1897.46$ in.

UG:

$A = (0.574128)(688)(1/2)$

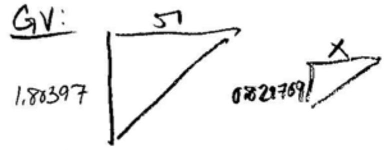
$A = 197.5$ in.

UV:

$A = (4.55552)(293)(1/2) + (5.5756)(344)(1/2) + (4.5552)(51) + (5.5756 - 4.55552)(51)(1/2)$

$A = 1072.88$ in.

GV:



$$\frac{51}{x} = \frac{1.80397}{0.829769}$$

$$x = \frac{(51)(0.829769)}{1.80397} = 23.4584$$

$A = (0.9742)(1/2)[344 + (51 - 23.4584)] - (0.829769)(1/2)(293 + 23.4584)$

$A = 49.6842$ in.

GH:

$A = (3.84363)(293)(1/2) + (6.3577)(344)(1/2) + (3.84363)(51) + (6.3577 - 3.84363)(51)(1/2)$

$A = 1915.57$ in.

VH:

$A = (0.5)(688)(1/2)$

$A = 172$ in.

AP:

$A = (1.51403)(688)(1/2)$

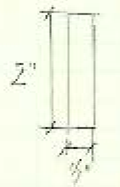
$A = 520.826$ in.

The Truss is symmetrical about member VH, therefore:

BQ = NAA	CD = ML	EF = KJ	GH = IH
BC = NM	RD = ZL	TF = XJ	AP = OBB
PQ = BB-AA	RS = ZY	TU = XW	
PB = BBN	DS = LY	FU = JW	
AB = ON	DE = LK	FG = JI	
QC = AAM	SE = YK	UG = WI	
QR = AAZ	ST = YX	UV = WV	
CR = MZ	ET = KX	GV = IV	

CPC Garage 11-15-10

Diagonal Cross Members



Moments of Inertia, I

$I = \frac{1}{12}(\frac{1}{2})(2)^3$
$I = \frac{1}{12}(\frac{1}{2})(2)^3$
$I = 0.333 \text{ in}^4$

Radius of gyration, r

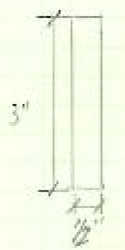
$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{0.333}{(2)(\frac{1}{2})}} = \sqrt{0.333} = 0.577321 \text{ in.}$

$\sigma_e = \frac{\pi^2 E}{(L/r)^2} = \frac{(\pi^2)(2.9 \times 10^7)}{(158/0.577321)^2}$

$\sigma_e = 28358.1$ psi

$\sigma_{cr} = (0.658^{\sigma_y/\sigma_e})\sigma_y$
$\sigma_{cr} = (0.658^{35000/28358.1})\,35000$
$\sigma_{cr} = 20879.5$ psi

$\sigma_{all} = \sigma_{cr}/F.S.$
$\sigma_{all} = 20879.5/1.67$
$\sigma_{all} = 12502.7$ psi



Moment of Inertia, I:
$I = \frac{1}{12}bh^3$
$I = (\frac{1}{12})(\frac{1}{2})(3^3)$
$I = 1.125 \text{ in}^4$

Radius of gyration, r.
$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{1.125}{(\frac{1}{2})(3)}} = \sqrt{0.75} = 0.866025$

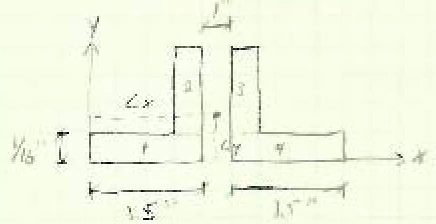
$\sigma_e = \frac{\pi^2 E}{(L/r)^2} = \frac{(\pi^2)(2.9 \times 10^7)}{(58/0.866025)^2} = 63812$ psi

$\sigma_{cr} = (0.658^{\sigma_y/\sigma_e})\sigma_y$
$\sigma_{cr} = (0.658^{35000/63812})\,35000$
$\sigma_{cr} = 27820.7$ psi

$\sigma_{all} = \sigma_{cr}/F.S.$
$\sigma_{all} = 27820.7/1.67$
$\sigma_{all} = 16659.1$ psi

MSCDC Garage 2

Vertical Double Angle Beams



$A = t(2a - t)$ t = thickness, a = length

$A = 1/16\,(2 \cdot 1.5 - 1/16)$

$A = 0.1836$

Due to symmetry $Cx = 4''/2 = 2''$

$Cx = 2''$

$$Cy = \frac{a^2 + at - t^2}{2(2a - t)} = \frac{1.5^2 + 1.5 \cdot 1/16 - 1/16^2}{2(2 \cdot 1.5 - 1/16)}$$

$Cy = 0.3983$

$I = \Sigma\ 1/12\ bh^3 + Ad^2$

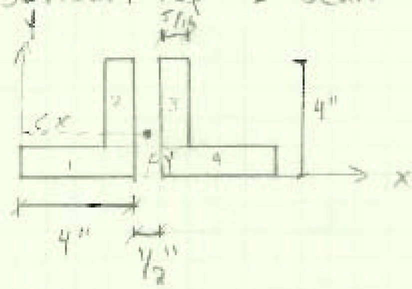
$$I_x = \left[\tfrac{1}{12}\,1.5 \cdot (1/16)^3 + (1.5 \times 1/16)(0.3983 - 1/32)^2\right] 2 + \left[\tfrac{1}{12} \cdot 1/16 \cdot 1.5^3 + (1.5 \times 1/16)\left(\tfrac{25}{32} - 0.3983\right)^2\right] \cdot 2$$

$I_x = 0.08797$

$$r = \sqrt{\frac{I}{A}} = \sqrt{\frac{0.08797}{0.1836}} = 0.692199$$

MSCDC Garage 3

Bottom / Top L-Beam (square)



radius of gyration = r

$r = \sqrt{I/A}$ A = cross sectional Area

I = moment of Inertia

$A = t(2a-t)$

t = thickness

a = length

Due to symmetry $C_x = 8.5/2$

$C_x = 4.25"$

$A = t(2a-t) = 5/16\,(2\cdot 4 - 5/16)$

$A = 2.402 \cdot 2$ ← because there are two beams.

$A = 4.804\ in^2$

$C_y = \dfrac{a^2 + at - t^2}{2(2a-t)} = \dfrac{4^2 + 4\cdot 5/16 - (5/16)^2}{2(2\cdot 4 - 5/16)}$

$C_y = 1.116"$

$I = \Sigma \frac{1}{12} bh^3 + Ad^2$

since 1 and 4 are equal

2 and 3 are equal

$I_x = [\frac{1}{12}(4)(5/16)^3 + (4 \times 5/16)(1.116 - 5/32)^2] \cdot 2 + [\frac{1}{12}(5/16)(59/16)^3 + (59/16 \times 5/16)(69/32 - 1.116)^2] \cdot 2$

$I_x = 2.3231 + 5.1055 = 7.4286$

$I_y = [\frac{1}{12} \cdot 4 \cdot (5/16)^3 + 4 \cdot 5/16\,(4.25 - 2)^2] \cdot 2 + [\frac{1}{12} \cdot 5/16 \cdot (59/16)^3 + (59/16 \cdot 5/16)(13/32)^2] \cdot 2$

$I_y = 13.6685$

$R_x = \sqrt{I_x/A}$

Main South CDC Maintenance Garage, 24 Kilby St

Member	Dimensions (in)	$A(in^2)$	$R_x(in)$	Length (in)	Euler's (psi)	Critical Stress (psi)	Allowable Stress (psi)	Allowable Force (lb)	Area Under Influence Line (in.)	Allowable Dead Load (lb/ft)	Axial Stress ANSYS (psi)
AB	4x4x5/16	4.8	1.24	38	304,770.68	33,357.46	19,974.53	95,877.74	-435.28	-2,643.22	-7,254.80
BC	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,188.46	-931.51	-15,494.00
CD	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,329.37	-832.77	-22,234.00
DE	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,556.23	-711.38	-27,477.00
EF	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,769.44	-625.66	-31,222.00
FG	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,897.46	-583.45	-33,469.00
GH	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,915.57	-577.93	-33,632.00
HI	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,915.57	-577.93	-33,632.00
IJ	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,897.46	-583.45	-33,469.00
JK	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	1,769.44	625.66	-31,222.00
KL	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,556.23	-711.38	-27,477.00
LM	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,329.37	-832.77	-22,234.00
MN	4x4x5/16	4.8	1.24	51	169,199.87	32,097.19	19,219.87	92,255.39	-1,188.46	-931.51	-15,494.00
NO	4x4x5/16	4.8	1.24	38	304,770.68	33,357.46	19,974.53	95,877.74	-435.28	-2,643.22	-7,254.80
PQ	4x4x5/16	4.8		51			20,958.10	100,598.88	743.19	1,624.33	7,254.80
QR	4x4x5/16	4.8		51			20,958.10	100,598.88	945.60	1,276.63	15,494.00
RS	4x4x5/16	4.8		51			20,958.10	100,598.88	1,257.74	959.81	22,234.00
ST	4x4x5/16	4.8		51			20,958.10	100,598.88	1,556.23	775.71	27,477.00
TU	4x4x5/16	4.8		51			20,958.10	100,598.88	1,769.44	682.24	31,222.00
UV	4x4x5/16	4.8		51			20,958.10	100,598.88	1,872.88	644.56	34,055.00
VW	4x4x5/16	4.8		51			20,958.10	100,598.88	1,872.88	644.56	34,055.00
WX	4x4x5/16	4.8		51			20,958.10	100,598.88	1,769.44	682.24	31,222.00
XY	4x4x5/16	4.8		51			20,958.10	100,598.88	1,556.23	775.71	27,477.00
YZ	4x4x5/16	4.8		51			20,958.10	100,598.88	1,257.74	959.81	22,234.00
ZAA	4x4x5/16	4.8		51			20,958.10	100,598.88	945.60	1,276.63	15,494.00
AABB	4x4x5/16	4.8		51			20,958.10	100,598.88	743.19	1,624.33	7,254.80
AP	3x1/2	1.5		47			20,958.10	31,437.15	520.83	724.32	29,768.00
BQ	3x1/2	1.5		58			20,958.10	31,437.15	544.41	692.95	30,719.00
CR	3x1/2	1.5		58			20,958.10	31,437.15	447.16	843.65	25,134.00
DS	3x1/2	1.5		58			20,958.10	31,437.15	347.79	1,084.70	19,548.00
ET	3x1/2	1.5		58			20,958.10	31,437.15	248.42	1,518.57	13,963.00
FU	3x1/2	1.5		58			20,958.10	31,437.15	149.05	2,530.97	8,377.90
GV	2x1/2	1		58			20,958.10	20,958.10	49.68	5,061.92	909.65
IV	2x1/2	1		58			20,958.10	20,958.10	49.68	5,061.92	909.65
JW	3x1/2	1.5		58			20,958.10	31,437.15	149.05	2,530.97	8,377.90
KX	3x1/2	1.5		58			20,958.10	31,437.15	248.42	1,518.57	13,963.00
LY	3x1/2	1.5		58			20,958.10	31,437.15	347.79	1,084.70	19,548.00
MZ	3x1/2	1.5		58			20,958.10	31,437.15	447.16	843.65	25,134.00
NAA	3x1/2	1.5		58			20,958.10	31,437.15	544.41	692.95	30,719.00
OBB	2x1/2	1.5		47			20,958.10	31,437.15	520.83	724.32	29,768.00
BP	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-326.00	**-391.57**	-49,911.00
CQ	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-299.50	-426.21	-42,232.00
DR	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-274.00	-465.88	-34,554.00
ES	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-248.50	-513.68	-26,875.00
FT	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-223.00	-572.42	-19,196.00
GU	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-197.50	-646.33	-8,512.30
HV	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-172.00	-742.15	-1,667.50
IW	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-197.50	-646.33	-8,512.30
JX	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-223.00	-572.42	-19,196.00
KY	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-248.50	-513.68	-26,875.00
LZ	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-274.00	-465.88	-34,554.00
MAA	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-299.50	-426.21	-42,232.00
NBB	3/2x3/2x1/5	0.56	0.696	30.5	149,001.62	31,722.68	18,995.62	10,637.55	-326.00	**-391.57**	-49,911.00
HU	2x1/2										-3,279.30
HW	2x1/2										-3,279.30
	E=	3E+07									
	Yield Strengt	35000	psi								
	Factor of Safe	1.67									

Appendix C: Area of Roofs within Combined Sewer System

n> 30
Assume normal distribution

Address	Roof Sq. Ft. (Approx.)
65 Tainter	31500
12 Queen	17700
26 Queen	22400
33,39,43 Hammond	26252
44 Hammond	45650
93 Grand	42050
662 Main	53532
857 Main	21675
888 Main	14601
689 Main	7000
95 Grand	41150
653 Main	12500
45 Grand	60348
49 Gardner	6068
674 Main	5400
701 Main	7650
845 Main	1842
875 Main	9792
19 Ripley	13450
64 Beacon	59250
98 Beacon	7125
18 Hammond	3255
35 Lagrange	4750
47 Lagrange	13095
50 Lagrange	5460
698 Main	6300
891 Main	3103
712 Main	6900
945 Main	9600
14 Gardner	3220
12 Hammond	792
68 Gardner	60840

24 Kilby	6000	
650 Main	5047	
660 Main	7015	
667 Main	8500	
709 Main	6080	
720 Main	3650	
895 Main	2916	
108 Beacon	4350	
22 Ethan Allen	8550	
868 Main	6640	
931 Main	3290	
46 Wellington	10850	
872 Main	3092	
880 Main	3740	
6 Ripley	3913	
25 Ethan Allen	3300	
9 Hammond	777	
64 Jackson	5537	
934 Main	3990	
45 Wellington	2135	
49 Wellington	3750	
36 Gates	2420	
23 Wellington	4640	
37 Wellington	2100	
1 Kilby	3000	
total	739532	
acres	17	34% of possible roof area
Avergae Roof Size	12974.24561	
Area of roof with in MS CSS	2075879.298	
	47 acers	10% of total acerage

Appendix D: Potential Site Charts

Rank	Address	Property Id #	Building description	Construction Material	Roof Sq. Ft. (Approx.)	Owner	Pipe Size
1	65 Tainter	06-33B-00007	Boys and Girls Club	Masonry/Steel	31500	The Boys & Girls Club	13"-18"
2	12 Queen	06-015-00006	UMass	Brick/Steel	17700	UMass Medical Center	9"-12"
3	26 Queen	06-015-0013A	Family Health Center	Brick/Steel	22400	UMass Medical Center	9"-12"
4	33,39,43 Hammond	06-032-00033	Factory	Steel, brick	26252	New Method Plating & Enameling	9"-12"
5	44 Hammond	06-33A-03+34	Factory		45650	Nettle LLC	9"-12"
6	93 Grand	07-003-00002	Old Factory	Brick	42050	Main South CDC	20"-28"
7	662 Main	03-014-00011	Supermarket	Masonry/Steel	53532	MGM Pena LLC	13"-18"
8	857 Main	06-034-00002	St. Peter's School	Brick	21675	Roman Catholic Bishop of Worcester	13"-18"
9	888 Main	06-037-08+20	Commercial	Masonry	14601	Arthur Mooradian, Trustee	9"-12"
10	689 Main	03-008-0004	Apartments/Commercial	Brick	7000	Sondatt B Prashad Trustee	13"-18"
11	95 Grand	07-003-00003	Old Factory	Brick	41150	Worcester EOEND	20"-28"
12	653 Main	03-009-00001	Apartments	Brick	12500	Hadley Apartments LLC	13"-18"
13	45 Grand	07-005-001-7	Apartments	Masonry/Brick	60348	Crystal Park Ltd Partnership	13"-18"
14	49 Gardner	06-33B-00011	ANC Tool Manufacturing	Steel	6068	South Garden Realty Inc	20"-28"
15	674 Main	03-014-00002	Apartment Building	Brick	5400	Worcester Lofts Limited Partnership	13"-18"
16	701 Main	03-008-00003	?	Brick	7650	PIP Foundation Inc	13"-18"
17	845 Main	06-034-00004	Dunkin' Donuts		1842	J & M Batista Family Limited	13"-18"
18	875 Main	06-33c-00015	Main South CDC	Brick/Concrete	9792	Clark University Trustees	13"-18"
19	19 Ripley	06-034-00012	Catholic School	Brick	13450	Crozier Inc.	9"-12"
20	64 Beacon	03-004-00002	Old Factory	Brick	59250	Vaios Theodorakos, Trustee	13"-18"
21	98 Beacon	03-001-00008	Commercial/Industrial	Brick	7125	Steven M Rothschild Trustee	8"
22	18 Hammond	06-034-00021	Sun Bridge Nursing Home	Brick	3255	Idak Convalescent Centers Inc.	9"-12"
23	35 Lagrange	03-001-00001	Industrial	Steel	4750	Joseph M & Stephen A Krosoczka	8"
24	47 Lagrange	03-001-0005	Industrial	Wood Frame/Brick	13095	Sem Tec Inc	8"
25	50 Lagrange	06-028-00014	Factory	Brick	5460	Joseph M & Stephen A Krosoczka	8"
26	698 Main	03-014-00032	Apartment & Commercial	Masonry & Brick	6300	Ediberto Santiago	13"-18"
27	891 Main	06-035-00027	Georges Flower Shop	Brick	3103	Raymond A. & Judith Levine	13"-18"
28	712 Main	06-17B-63+78	Apartment & Church	Brick	6900	Wellington Company	13"-18"
29	945 Main	07-006-00025	Byram Healthcare	Masonry	9600	Clark University Trustees	13"-18"
30	14 Gardner	07-001-00004	C & V auto body	Brick	3220	Lisa D Servant	13"-18"
31	12 Hammond	06-034-00019	Alfred and Sons Funeral Home	Brick	792	Alfrod Roy and Sons Inc.	13"-18"
32	68 Gardner	07-003-0003A	Industrial	Masonry	60840	68 Gardner LLC	30"+
33	24 Kilby	06-33B-00010	CDC Garage	Masonry	6000	Main South CDC	9"-12"
34	650 Main	03-014-00001	Commercial	Masonry	5047	Anastasios Karamanos	13"-18"
35	660 Main	03-014-00003	Apartments	Masonry	7015	Community Renewal, Inc	13"-18"
36	667 Main	03-009-00019	Apartments	Masonry	8500	General Realty Corp	13"-18"
37	709 Main	03-008-00002	Apartments/Retail	Masonry	6080	Julio Romero	13"-18"
38	720 Main	06-17B-00115	Apartment Building	Brick	3650	Chestnut Renewal Cooperation	13"-18"
39	895 Main	06-035-00028	Moynihan's Pub	Brick/Masonry	2916	Goerdon J Turpin	13"-18"
40	108 Beacon	06-028-00005	Commercial/Industrial	Brick	4350	HW Beacon LLC	8"
41	22 Ethan Allen	06-17B-13-15	Apartments	Brick	8550	Wellington Company	8"
42	868 Main	06-037-00022	Hampton Properties/Commercial	Masonry	6640	Quek Kevin Ying Xuan	13"-18"
43	931 Main	07-006-00034	St. Peter's Church	Masonry	3290	Roman Catholic Bishop of Worcester	13"-18"
44	46 Wellington	03-015-15+27	Apartments	Brick	10850	Wellington Company	9"-12"
45	872 Main	06-037-00048	Chinese Restaurant	Masonry	3092	Zi Feng Li	13"-18"
46	880 Main	06-037-00030		Masonry	3740	Cultural Ctr Hrisohorafiton	13"-18"
47	6 Ripley	06-33C-13+14	CDC Apartments	Brick	3913	Main South CDC	9"-12"
48	25 Ethan Allen	06-17A-00017	Apartments	Brick	3300	Wellington Company	8"
49	9 Hammond	06-030-00014	Real Time Court Reporting	Wood	777	All Realtime Realty LLC	13"-18"
50	64 Jackson	03-001-00015	Sprint Building	Masonry	5537	US Sprint Communications Company	9"-12"
51	934 Main	06-042-00023	Apartments/Business	Wood/Brick	3990	Clark University Trustees	13"-18"
52	45 Wellington	06-17B-00069	Apartments	Brick	2135	Chestnut Renweal Cooperation	9"-12"
53	49 Wellington	06-17B-00071	Apartments	Brick	3750	Chestnut Renweal Cooperation	9"-12"
54	36 Gates	07-007-00010	Apartments	Wood/Masonry	2420	Main South CDC	8"
55	23 Wellington	06-17B-31+46	Apartments	Brick	4640	Wellington Company	13"-18"
56	37 Wellington	06-17B-00047	Apartments	Brick	2100	Chestnut Renweal Cooperation	13"-18"
57	1 Kilby	06-035-00010	Appartment	Wood	3000	Garry G. Dutram	9"-12"